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Advanced Air Revitalization System Testing
Final Report

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**Advanced Air Revitalization System Testing
Final Report**

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**Prepared for
Ames Research Center
under Contract NAS-210961**



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Space Administration**

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. at Cleveland, Ohio under Contract NAS2-10961, during the period of May, 1981 through June, 1983. The Program Manager was Dr. Dennis B. Heppner. The personnel contributing to the program and their responsibilities are outlined below:

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LIST OF ACRONYMS

A/D	Analog/Digital
ARS	Air Revitalization System
ARX-1	One-Person, Experimental, Air Revitalization System
ASU	Air Supply Unit
B-CRS	Bosch Carbon Dioxide Reduction Subsystem
CCA	Coolant Control Assembly
CHCS	Cabin Humidity Control Subsystem
C/M I	Control/Monitor Instrumentation
CPU	Central Processing Unit
CRS	CO ₂ Reduction Subsystem
DARS	Data Acquisition and Reduction System
ECLSS	Environmental Control/Life Support System
EDC	Electrochemical Depolarized CO ₂ Concentrator
EDCM	EDC Module
FCA	Fluids Control Assembly
FSU	Fluids Supply Unit
LEO	Low-Earth Orbit
M/EA	Mechanical/Electrochemical Assembly
NSS	Nitrogen Supply Subsystem
OGS	Oxygen Generation Subsystem
PID	Proportional, Integral, Differential
PROM	Programmable Read Only Memory
PWM	Pulse Width Modulator
RTD	Resistance Thermal Device
S-CRS	Sabatier Carbon Dioxide Reduction Subsystem
SFE	Static Feed Electrolyzer
SFWM	Static Feed Water Electrolysis Module
SFWES	Static Feed Water Electrolysis Subsystem
STS	Space Transportation System
3-FPC	Three-Fluids Pressure Controller
TSA	Test Support Accessories
WHS	Water Handling Subsystem

SUMMARY

Definition of a low-earth orbit Space Station is currently underway by the National Aeronautics & Space Administration. One major element of this activity is the definition of the technology required to support such a Space Station. Technology readiness is being assessed for all the functional areas of the Space Station. One of the most important functional areas is the Environmental Control/Life Support System. Within this system a key portion of it is the air revitalization system which is that hardware required to reclaim the oxygen from man's metabolic carbon dioxide and perspired water and provide breathing oxygen. Technology readiness of the regenerative air revitalization system must be demonstrated.

A program to develop and test a one-person, breadboard, experimental Air Revitalization System has been underway at the National Aeronautics & Space Administration and Life Systems, Inc. for the past several years. This facility (Figure 1) represents the first totally integrated, self-contained air revitalization system at any person level that is totally operated with its own control monitor instrumentation and will operate with a one-button startup. The facility is unique in the United States. The work reported herein is a portion of the overall program. It describes the upgrades and the improvements made to this system. It also covers the additional testing under conditions similar to those that will be encountered in the Space Station.

Several modifications were made to the existing facility. The electrochemical CO₂ removal module was upgraded to incorporate unitized electrode/matrix cores which were shown to have major performance improvements. A new 12-cell water electrolysis module was fabricated and installed. Upgrades were made to the automatic control and monitor instrumentation including installation of new analog/digital converter boards and improvements in the signal conditioning. The capability for cyclic operation of the system to simulate cyclic power availability (i.e., light/dark portions of low-earth orbit) was added.

In the test support accessories area, several additions were made. Provisions for simulating variations in spacecraft air carbon dioxide and humidity levels and spacecraft coolant supply temperatures were implemented. The capability for automatic data acquisition with a computer based storage system was also added.

The testing phase consisted of completion of 60 days of total integrated operation at nominal, and varying parametric and cyclic conditions. Major findings were that the function of carbon dioxide removal, carbon dioxide reduction, oxygen generation, cabin humidity control and the associated water handling can be and were successfully designed and built to work together under single automatic computer control. Predicted behavior was verified in most cases.

In addition to the activities cited above, two parallel tasks were undertaken during this program. One involved the preliminary design of an air revitalization system for the Space Station at the four-person level. The other task involved a design of future environmental control and life support automated control concepts. These activities are documented in separate reports.

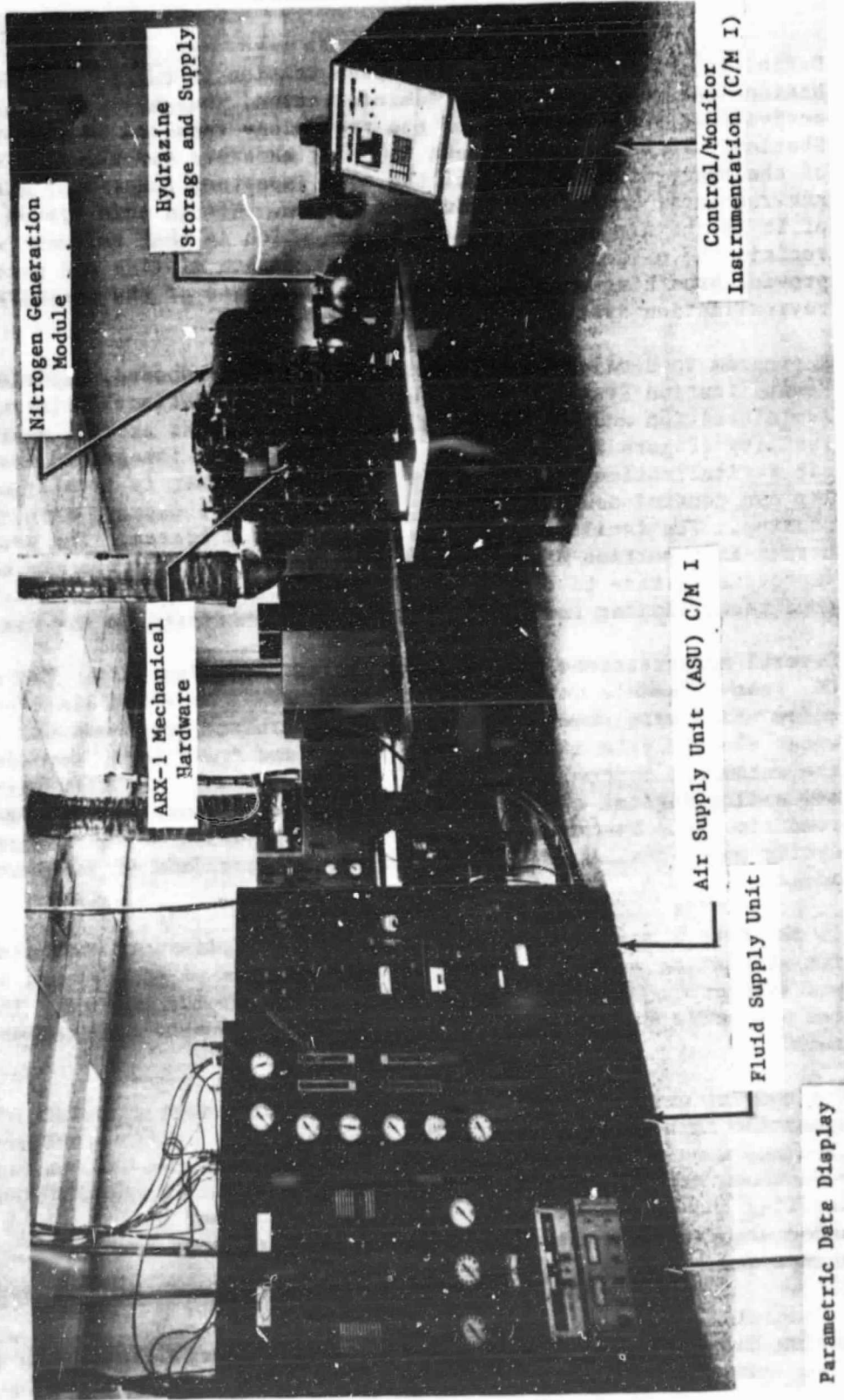


FIGURE 1 ARX-1 TEST FACILITY

It is concluded from the results reported herein that a totally integrated air revitalization system is a viable approach for atmospheric control aboard a manned Space Station. Continued development of the integrated approach and its related technology is recommended to further improve the design concepts, decrease equivalent weight and increase hardware reliability. Successful completion of this development will produce timely technology necessary to implement future regenerative Environmental Control/Life Support system programs.

ACCOMPLISHMENTS

Key program accomplishments are:

- Demonstrated one-button startup of a complex physiochemical system without manual intervention.
- Extended by 1,350 h the total period that the one-person breadboard air revitalization system has been under test.
- Implemented capability for varying process air carbon dioxide (CO_2) partial pressure and humidity and coolant source that simulate realistic space vehicle interfaces.
- Obtained dynamic system performance response on the interaction of subsystems, particularly the Electrochemical CO_2 Concentrator (EDC), Sabatier CO_2 reduction and oxygen (O_2) generation subsystems.
- Gained additional integration technology knowledge and experience during which some key observations were made.
- Upgraded the EDC module (EDCM) of the breadboard system with the latest unitized core technology for the liquid-cooled cell.
- Generated a preliminary design for a regenerative air revitalization system for the Space Station.

INTRODUCTION

Regenerative processes for the revitalization of spacecraft atmospheres are essential for making a long-term Space Station a reality.^(1,2) The alternative, open-loop Shuttle technology, is uneconomical because of the total amount of supplies (and their launch costs) that need to be taken into space. The subject program continued the development of an integrated air revitalization system based on regenerative techniques. These techniques allow for the efficient removal of CO_2 from a spacecraft's cabin atmosphere, CO_2 reduction with hydrogen (H_2) and O_2 recovery through water electrolysis.

(1,2) References are cited at end of report.

Background

The function of a regenerative Air Revitalization System (ARS) is to (1) remove the metabolically generated CO_2 and water vapor, (2) recover the O_2 contained in the recovered CO_2 and water for metabolic consumption by the crew, make up for O_2 lost because of Space Station leakage and O_2 consumed in the process of CO_2 removal and (3) provide H_2 for the reduction of CO_2 to form water and for that consumed in the CO_2 concentration process. The control of ambient relative humidity and partial pressure of O_2 is a desirable function.

A considerable amount of NASA Environmental Control/Life Support System (ECLSS) technology, including ARS technology, has been focused on development of specific subsystems to accomplish each of the major functions of the ECLSS and the ARS in particular. These subsystems developments include the Electrochemical Depolarized CO_2 Concentration (EDC) Subsystem, ⁽³⁻⁶⁾ Static Feed Water Electrolysis Subsystem (SFWS), ^(7,8) CO_2 Reduction Subsystem (CRS) ^(9,10) and Nitrogen Supply Subsystem (NSS) ⁽¹¹⁾. The focus on subsystems allows concentrating effort on developing the specific technology for each ARS function. A disadvantage, however, is the lack of knowledge concerning integration of the various subsystems and their interactions. Integration simplifies process hardware because duplicate components can be eliminated. Other reasons are listed in Table 1. Integration is needed for the Space Station's air revitalization function.

A program which resulted in the integration of subsystems to provide the air revitalization function was accomplished under various efforts beginning in 1976. Life Systems, with the support of NASA, defined, designed, fabricated and tested an integrated ARS with its automated process control and monitor instrumentation. ^(4,12,13) This development was at the one-person breadboard level, called the ARX-1. It addressed for the first time many of the technology gaps that existed between the isolated subsystems approach and an integrated approach. It also demonstrated the further need to perform additional development at the integrated level.

Initial development testing with the ARX-1 indicated the successful operation with a one-button startup from a centralized control and monitor instrumentation. The subject program further developed and tested the ARX-1. Conclusions drawn from the initial testing showed that (1) the integrated approach is sound (2) great hardware and process control simplification can be achieved, (3) some components remain to be developed; however, these are of a minor nature, and (4) there are no major unknowns in the design and operation of such a system.

Program Objectives

The overall objectives of the program reported on herein were to:

1. Refurbish, modify and upgrade the breadboard one-person ARX-1 test facility and its Test Support Accessories (TSA).

TABLE 1 REASONS FOR INTEGRATED SYSTEM DEVELOPMENT AND TESTING

- Eliminates duplicate components, which are not needed when the system is considered as a unit and not as a collection of subsystems.
- Accumulates components and parts which are common throughout system, e.g., water handling, in one centralized location.
- Imposes interaction dynamics on components by using actual end-item similar plumbing and ducting.
- Permits realistic, end-application startup demonstration with one, centralized C/M I.
- Permits use of common facilities, e.g., spacecraft coolant, purge N₂, vacuum.
- Provides for real-life test conditions/interfaces.
- Reduces expendables.

2. Design, fabricate and assemble added development hardware to support the testing program.
3. Demonstrate integration concepts through actual operation of a functionally-integrated ARS.
4. Test the integrated system under conditions similar to those expected in the end application.
5. Accumulate the experience and knowledge of operating an integrated ARS to allow future Space Station ARS designs to proceed.

Program Organization

To meet the above objectives, the program was divided into five major tasks plus documentation and program management functions. The tasks were:

1. Refurbish, modify and upgrade the ARX-1 hardware developed under previous NASA contracts. The refurbishment included both the hardware and software elements of the ARX-1 Control and Monitor Instrumentation (C/M I).
2. Conduct a parametric test program consisting of checkout, shakedown and parametric tests. Parametric testing included variations of pCO_2 and dew point of the simulated cabin air and of the coolant supply temperature at the interface to the ARX-1.
3. Conduct cyclic testing to simulate low-earth orbit (LEO) day/night timeframes. The cyclic testing included checkout, shakedown and design verification tests.
4. Prepare a preliminary design study of concepts for ECLSS control and monitor instrumentation. The activities of this task culminated in the preparation of mini-design/recommendations report.
5. Prepare, in a separate report, a preliminary design of an Air Revitalization System for future Space Station application.

Report Organization

This Final Report covers the work performed during the period, May, 1981 through June, 1984. Portions of the work performed under this program are covered in greater detail in two separate reports. (14,15)

The following five sections of this report represent the technical results and are grouped according to (1) ARX-1 system description, (2) TSA, (3) system testing, (4) ECLSS C/M I design and (5) ARS preliminary design. The last two sections are synopses of other referenced reports. These sections are then followed by Conclusions and Recommendations based on the work performed and by References.

ARX-1 SYSTEM DESCRIPTION

The block diagram of a regenerative ARS for the control of a Space Station atmosphere is shown in Figure 2. Shown are the three principal subsystems needed to remove CO_2 from and provide O_2 to the crew space. These are the EDC, the Sabatier CO_2 Reduction Subsystem (S-CRS) and the Oxygen Generation Subsystem (OGS). In addition, the Cabin Humidity Control Subsystem (CHCS) is used to supply conditioned air to the EDC and to remove the metabolic and EDC moisture from the cabin air. A water handling subsystem collects, stores and distributes liquid water within the ARS. Finally, a NSS using decomposition of hydrazine (N_2H_4) provides for N_2 lost through cabin leakage and extra H_2 to be used by the S-CRS. The breadboard ARX-1 incorporates a NSS. However, for the present program, the N_2 generating components were not operated.

A one-person regenerative ARS configured in this manner would have the characteristics for fluid production/consumption as shown in Table 2. The metabolic requirements for CO_2 removal and O_2 generation and the O_2 leakage rates are based on per person daily average values for a baseline Space Station. The ARX-1 mechanical/electrochemical assembly (M/EA) hardware sized for these design flows was developed into the engineering breadboard assembly shown in Figure 3. The detailed mechanical schematic of the ARX-1 is given in Figure 4 while the nominal conditions for one-person operation are given in Table 3.

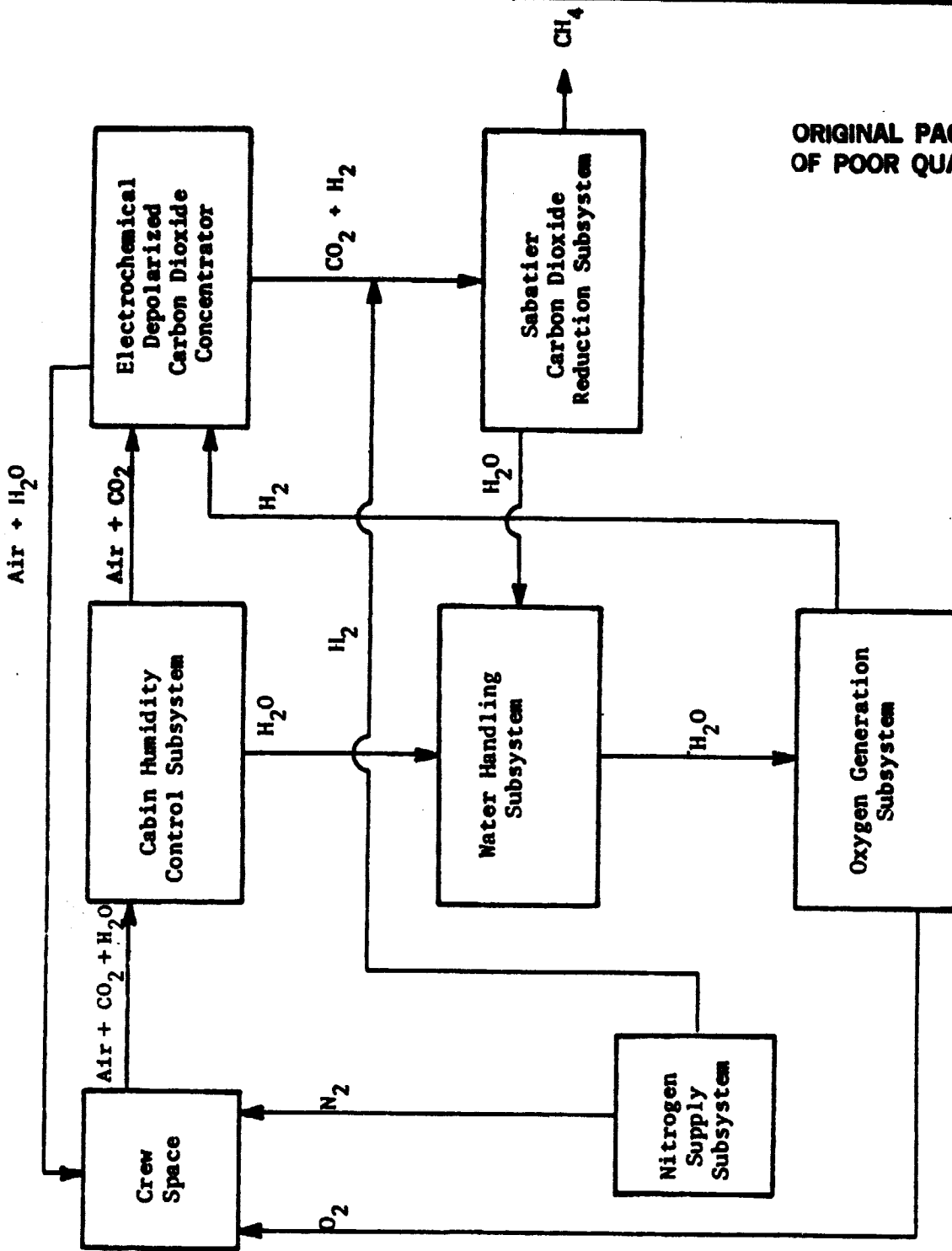
The system operating modes and mode transitions are shown in Figure 5. The arrows indicate the transitions which are permitted under the instrumentation control. In the normal mode the ARX-1 performs its intended air revitalization functions. In the shutdown mode these functions are inoperative but the system is powered and all sensors are working. The system is in this mode upon application of electrical power. During purge, all H_2 lines are flushed with N_2 . In the standby mode the system is powered and maintained at operating temperatures and pressures. It is this mode that was utilized alternately with the normal mode during cyclic testing. In the unpowered mode, no electrical power is applied to the system and there are no fluid flows.

ARX-1 Subsystems Component Descriptions

The principal ARX-1 subsystem process components identified in Figure 3 are described below.

Cabin Humidity Control

The primary key component in the CHCS is a microgravity-compatible condensing heat exchanger shown in Figure 6. This unit utilizes liquid coolant flowing through tubes perpendicular to heat transfer fins and process air flow. Moisture condensing on the fins is driven by air flow to a final row of tubes which do not carry coolant. All condensate and a portion of the process air are drawn into these tubes through small holes. The required suction is created by a small fan downstream of a liquid/gas separator where the condensate is removed. The liquid-free air is discharged by the fan back into the process air flow downstream of the heat exchanger.



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FIGURE 2 AIR REVITALIZATION SYSTEM BLOCK DIAGRAM

TABLE 2 OVERALL ARX-1 DESIGN CHARACTERISTICS

Crew Size	1
CO ₂ Removal Rate, kg/d (lb/d)	1.00 (2.20)
O ₂ Generation Rate, kg/d (lb/d)	1.64 (3.60) ^(a)
Humidity Condensate Removal Rate, kg/d (lb/d)	1.82 (4.01)
Liquid Water Production Rate, kg/d (lb/d)	1.24 (2.73)
Methane Production Rate, kg/d (lb/d)	0.35 (0.78)

^(a) Consists of 0.84 kg/d (1.84 lb/d) O₂ metabolic, 0.43 kg/d (0.94 lb/d) O₂ for the CO₂ removal process and 0.37 kg/d (0.82 lb/d) O₂ for leakage makeup requirements.

CHCS Heat Exchanger

Sabatier Reactor

EDC Module

NSS Module

OGS Module

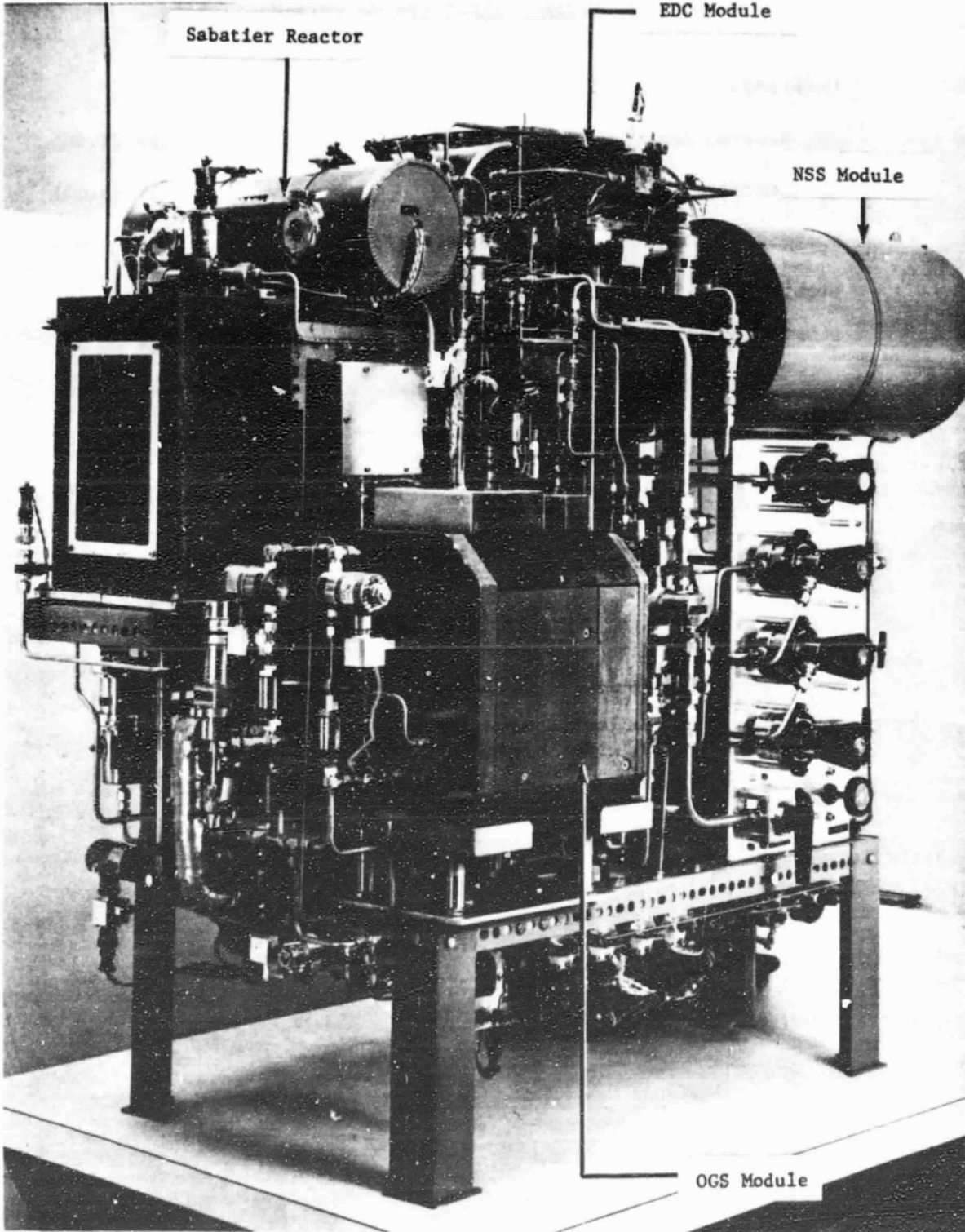


FIGURE 3 ARX-1 MECHANICAL HARDWARE

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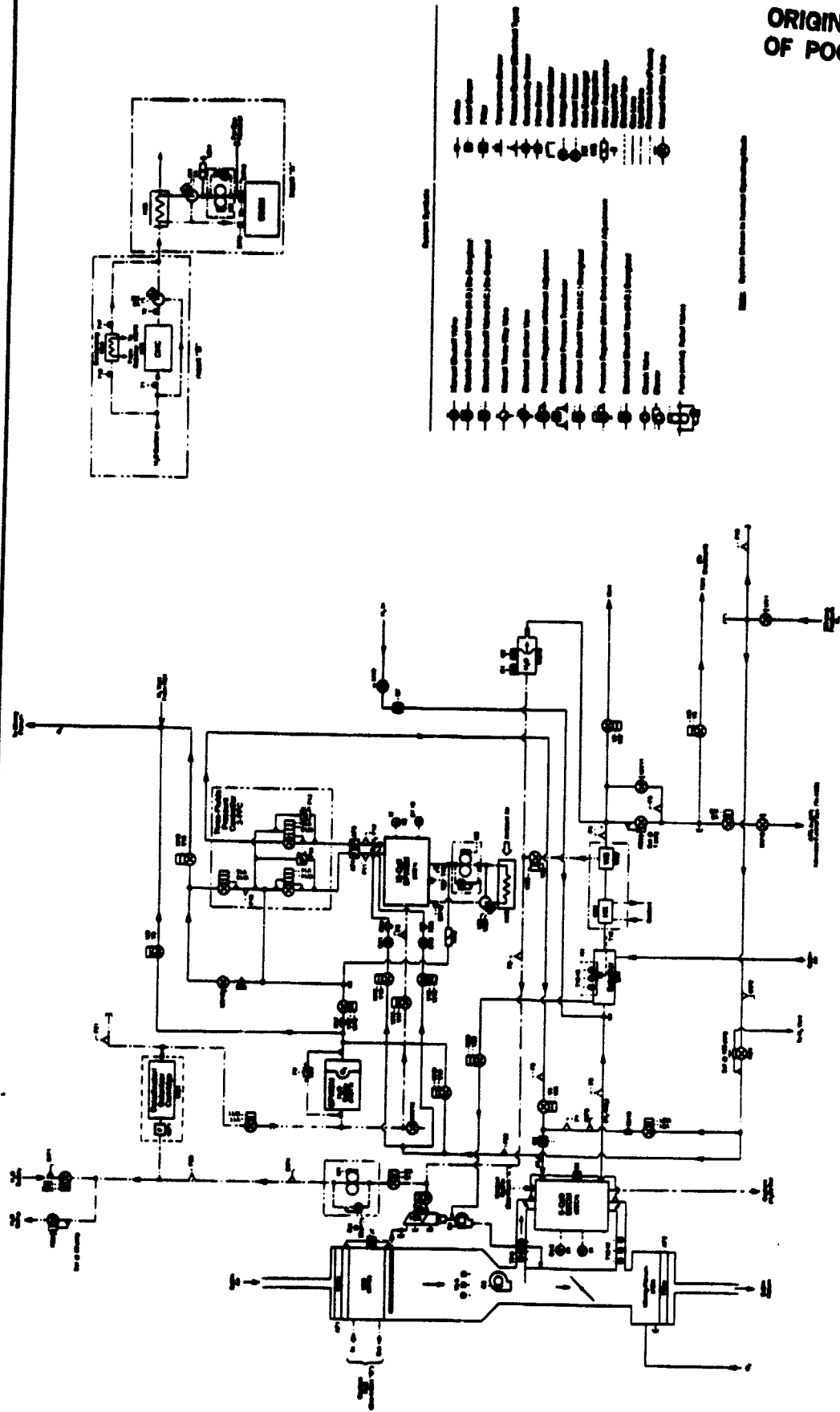


FIGURE 4 AXI-1 MECHANICAL SCHEMATIC

TABLE 3 ARX-1 NOMINAL OPERATING CONDITIONS

CO₂ Removal (EDC)	
Number of Cells	6
CO ₂ Removal Rate, kg/d (lb/d)	1.0 (2.2)
Current, A	9.9
Current Density, mA/cm ² (ASF)	22.6 (21)
Cell Voltage, V	0.40
Air Inlet Temperature, K (F)	287 to 294 (60 to 70)
Pressure, kPa (psia)	101 (14.7)
Air Flow, dm ³ /min (scfm)	305 (10.8)
pCO ₂ , Pa (mm Hg)	400 (3.0)
CO ₂ Removal Efficiency, %	84
O₂ Generation (SFWE)	
Number of Cells	12
Current, A	19.0
Current Density, mA/cm ² (ASF)	204 (190)
Average Cell Voltage, V	1.70
Module Temperature, K (F)	339 (150)
Pressures, kPa (psia)	
H ₂ O Feed, kPa (psia)	1,140 (165)
O ₂	1,163 (168)
H ₂	1,157 (167)
H ₂ -to-H ₂ O Differential	17.2 (2.5)
O ₂ -to-H ₂ O Differential	22.7 (3.3)
N ₂ Purge, kPa (psia)	1,170 (170)
Flow Rates, kg/d (lb/d)	
H ₂ O Feed	1.84 (4.05)
O ₂ Product	1.64 (3.60)
H ₂ Product	0.20 (0.45)
CO₂ Reduction (S-CRS)	
H ₂ Inlet Flow, cm ³ /min (lb/d)	1,700 (0.43)
CO ₂ Inlet Flow, cm ³ /min (lb/d)	380 (2.20)
Inlet Volumetric Flow Ratio, H ₂ /CO ₂	4.5
CH ₄ Outlet Flow, cm ³ /min (lb/d)	362 (0.78)
Water Outlet Flow, cm ³ /min (lb/d)	0.56 (1.71)
Reactor Temperature, K (F)	644 (700)
Heater Temperature, K (F)	644 to 755 (700 to 900)
CO ₂ Reduction Efficiency, %	95
H ₂ Conversion Efficiency, %	85
Humidity Control (CHCS)	
Water Removal Rate, kg/d (lb/d)	2.30 (5.07)
Cabin Air Flow, m ³ /min (cfm)	2.8 (100)
Cabin Air Temperature, K (F)	286 to 300 (65 to 80)
Cabin Min. Dew Point Temperature, K (F)	279 (42.5)
Cabin Max. Relative Humidity, %	90
Nominal Latent Heat Removed, W (Btu/h)	61.5 (210)
Nominal Sensible Heat Removed, W (Btu/h)	521 (1,780)

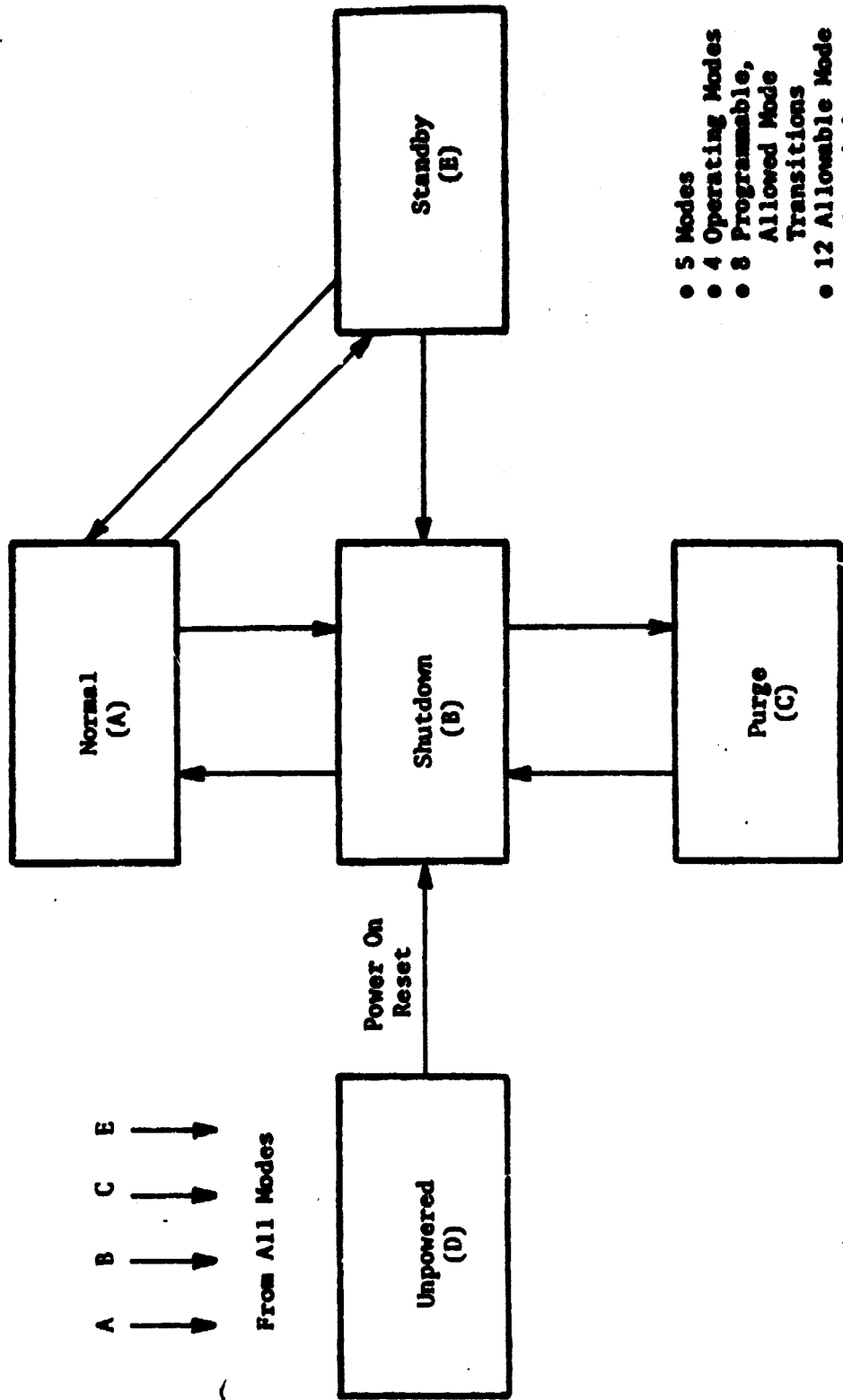


FIGURE 5 OPERATING MODES AND ALLOWABLE MODE TRANSITIONS

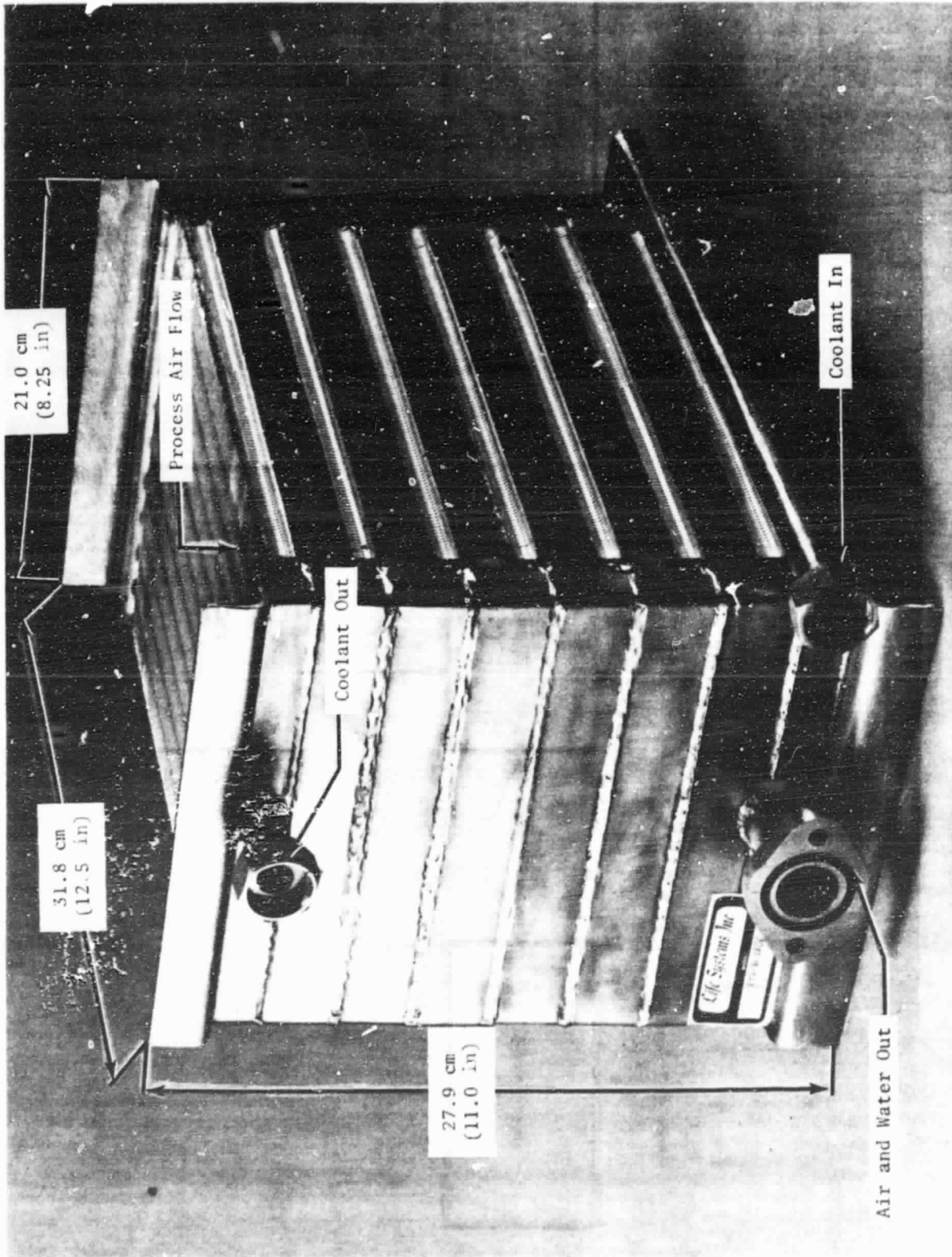


FIGURE 6 ONE-PERSON CAPACITY CONDENSING HEAT EXCHANGER

Use of a diverter valve in the coolant loop to the heat exchanger permits control of coolant temperature at constant flow rate through the heat exchanger. The exiting process air dew point temperature can then be controlled by the coolant temperature. In the ARX-1, $1.7 \text{ m}^3/\text{min}$ ($60 \text{ ft}^3/\text{min}$) of process air flow is maintained at a nominal process dew point of 285 K (54 F).

CO₂ Concentration

The key component in the CO₂ removal subsystem is a liquid-cooled EDCM shown in Figure 7. This module contains six electrochemical cells which perform the function of CO₂ removal, and in the process, produce electrical power. The DC electrical power produced by the EDCM is used to offset the power consumed by the water electrolysis module in the OGS. A power sharing control circuit provided in the C/M I performs this function.

CO₂ Reduction

An air-cooled Sabatier reactor is the heart of the S-CRS. The reactor is shown in Figure 8. The exiting H₂/CO₂ mixture from the EDCM is converted to methane (CH₄) and water vapor via an exothermic reaction. Catalysts promote the reaction which occurs at 644 K (700 F). The Sabatier exhaust, primarily CH₄ and water vapor, flows to a condenser/separator where water is removed. The remaining gas is vented overboard.

Oxygen Generation

A liquid-cooled, 12-cell static feed water electrolysis module (SFWEM) shown in Figure 9 is the key component of the OGS. Within each electrolysis cell, H₂ is produced at the cathode and O₂ at the anode. A three-fluids pressure controller is used to maintain the pressure of the O₂, H₂ and the water feed all with respect to absolute and with respect to each other.

Miscellaneous Hardware

Besides the major components that are identified above, several minor components including liquid/gas separators, fans, check valves, pumps, diverter valves, solenoid valves, hand valves, regulators, orifices, plumbing and structural parts comprise the mechanical assembly of the ARX-1. The total of these components weighs approximately 144 kg (316 lb) and together with this framework and its packaging framework occupies the volume of 0.91 m^3 (32 ft^3). The dimensions of the ARX-1 mechanical assembly shown in Figure 3 are 117x76x102 cm (46x30x40 in).

Several hardware modifications/upgrades were made to the M/EA. They are identified in Table 4. The principal ones involved the EDCM and SFWEM, including the use of Fluorinert as module coolant. This non-conductive coolant was added to provide electrical inter-cell isolation of the modules. Besides the upgrades listed, most other components were inspected and individually checked (e.g., solenoid valves to ensure operation, etc.) before testing began.

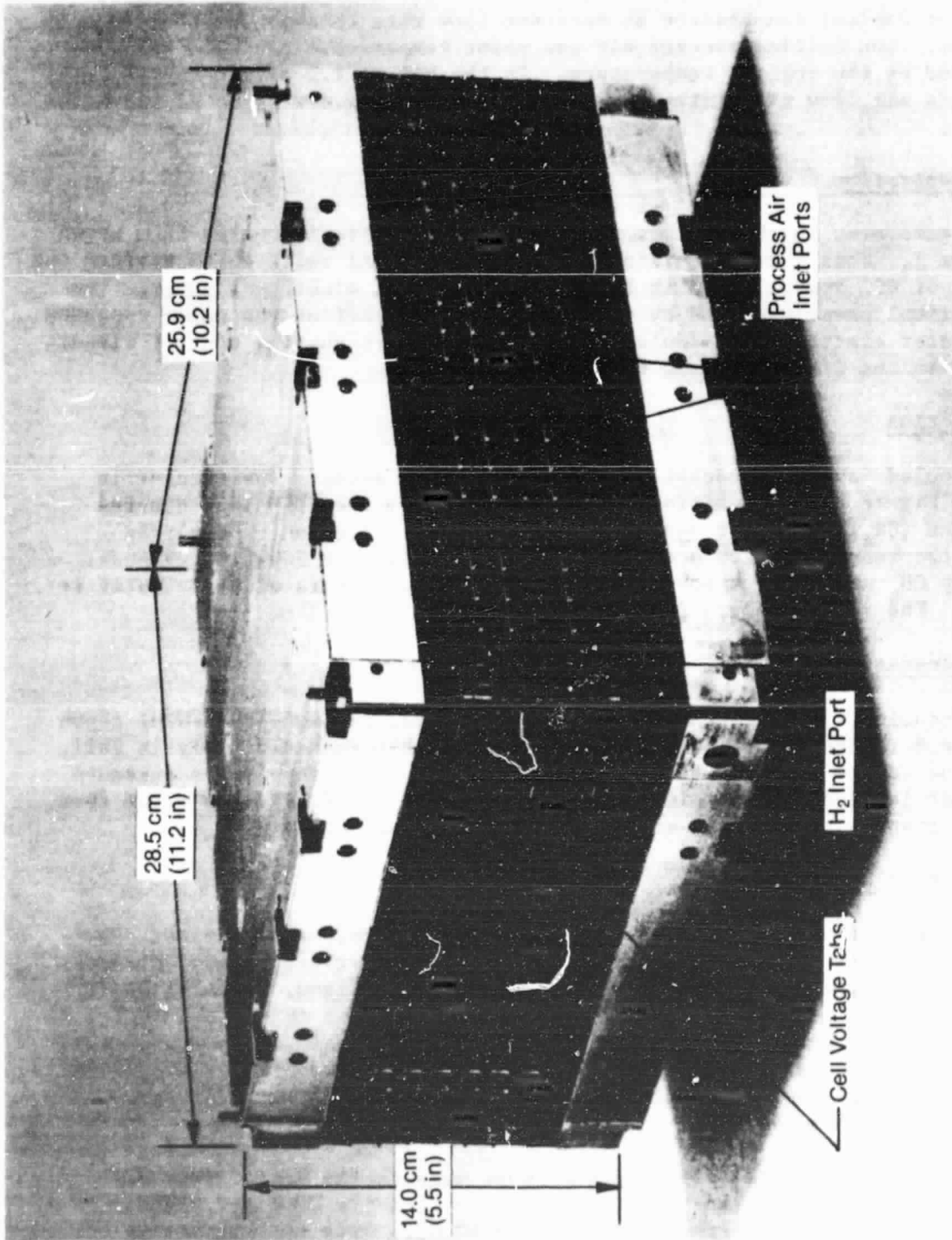


FIGURE 7 LIQUID-COOLED EDM

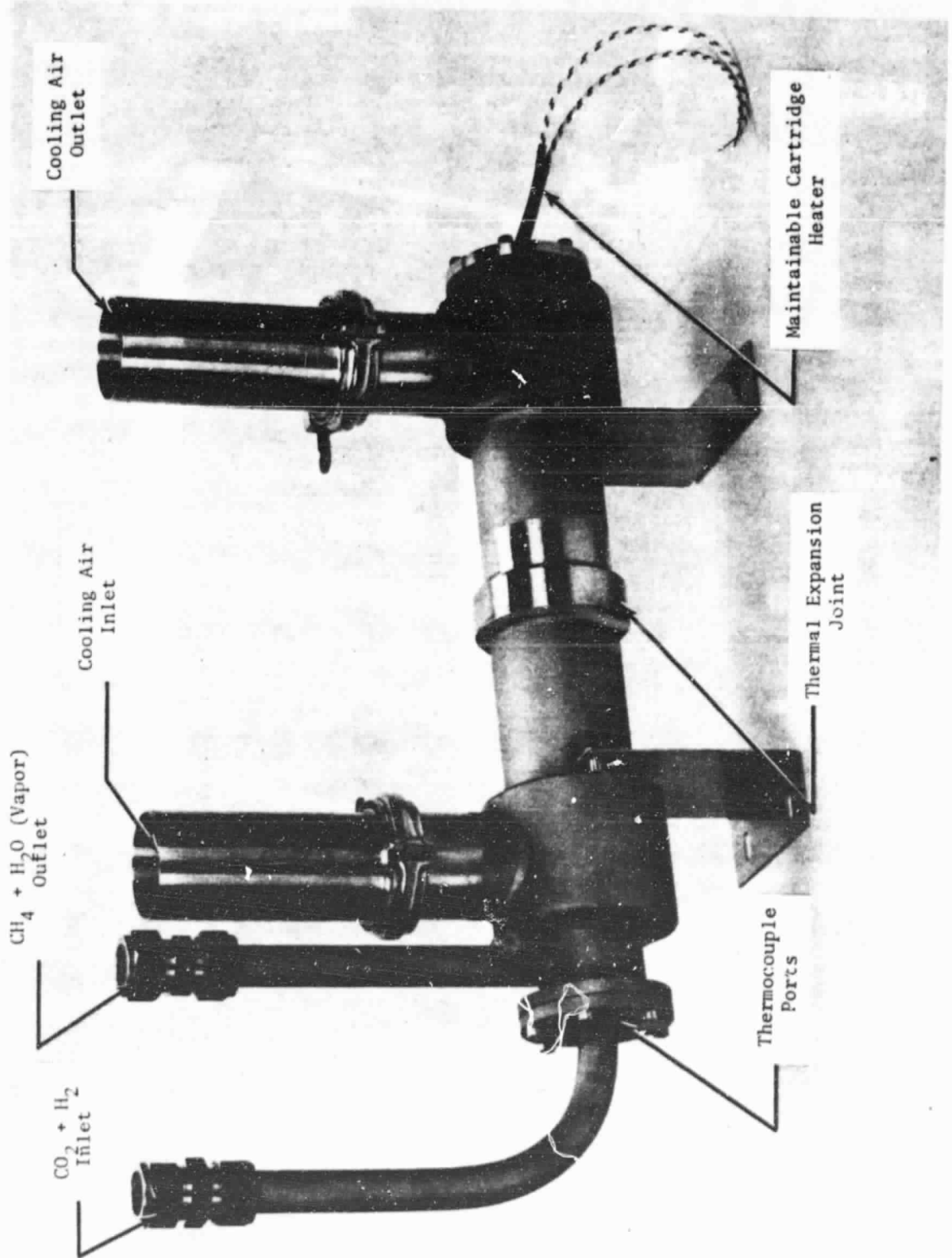


FIGURE 8 ONE- TO THREE-PERSON SABATIER REACTOR

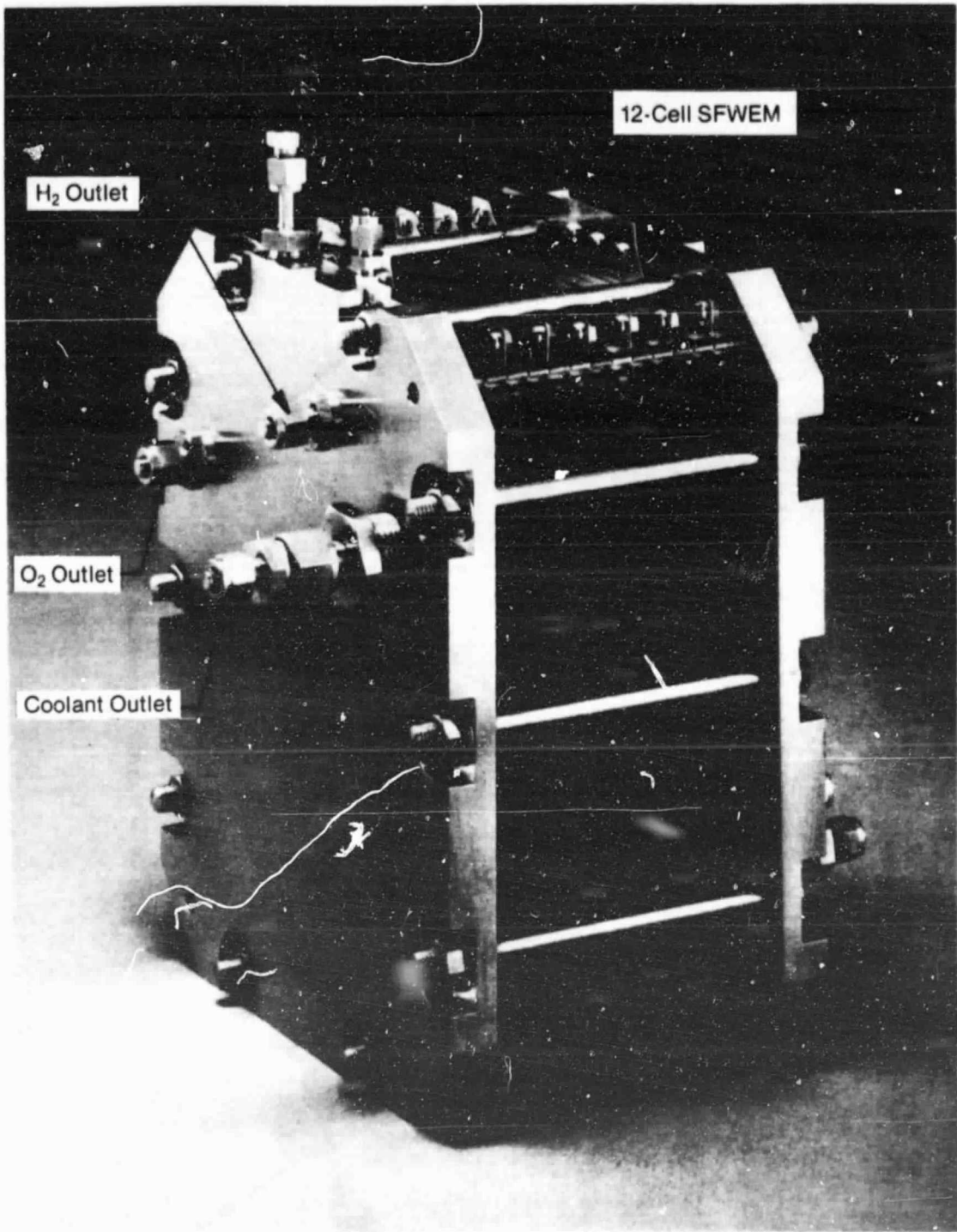


FIGURE 9 STATIC FEED WATER ELECTROLYSIS MODULE

TABLE 4 ARX-1 M/EA HARDWARE MODIFICATIONS/UPGRADES

- Refurbished EDCM with unitized cores.
- Rebuilt SPWEM - Advanced electrodes.
- Replaced failed Sabatier heater (H1) and thermocouple (T016).
- Changed coolant in EDCM and SPWEM from water to Fluorinert.
- Eliminated all Nitrogen Generation Module (NGM) interfaces. Disconnected (electrically only) valves.
- Removed water storage tank (WST2) to simulate spacecraft storage tank operation. Added TSA pump which is operated only during WST1 water refill.
- Replaced 3-FPC with improved version. Required new plumbing interfaces.
- Eliminated vacuum pump (was needed for NGM operation only).
- Upgraded air/water screen separator.
- Refurbished Sabatier condenser/separator (WS2).
- Referenced accumulator WA2 to system pressure.
- Added inlet and outlet valves to EDCM process air ducting to isolate module during dark cycle of cyclic operation.

ARX-1 Control/Monitor Instrumentation

The C/M I required to operate the ARX-1 with total automatic one-button startup button capability is shown in Figure 10. This unit contains the following: power supplies, signal conditioning cards for all system sensors and actuator driver relays, power sharing electronics for operating the SFWEM and EDCM together or separately, minicomputer, CRT screen and controller, a dedicated keyboard and all software to provide for process control, fault detection and mode transition capability. Table 5 summarizes the C/M I physical characteristics as well as those of the M/EA.

C/M I Hardware

Several improvements and upgrades were made to the C/M I hardware. These are identified in Table 6. The analog to digital (A/D) and the A/D expander boards were each replaced with an upgraded A/D board that Life Systems had develop for its Series 100A instrumentation. A water electrolysis current shutdown relay was added to prevent potentially full current flow to the SFWEM caused by a failure of the EDCM/SFWEM current controller card. Signal conditioning for the 3-FPC pressure sensors was upgraded along with replacement of actual sensors. Wiring was added to interface the Data Acquisition and Reduction System (DARS) with the C/M I and the TSA parametric display for selected sensors. The replacement of the A/D boards and other upgrades improved the reliability of the C/M I to the extent that during the testing no failures of the C/M I hardware (or software) caused test interruptions.

In addition, the capability for cyclic operation was added as shown in the block diagram of Figure 11. A square wave timing signal (54 min on/36 min off) was generated by the internal computer clock and outputted through the A/D board to the Cyclic Testing Controller. This device provided cycle indication (light or dark), mode selection (light, dark or automatic) and override capability. In the automatic mode, the timing signal was sent to the "Normal" and Standby" front panel switches and simulated pressing of the switches. The actual initiation of the light/dark cycle and the transitions were handled through software.

Isolation of the EDCM to process air during the dark period was implemented by motor-driven isolation valves. Two motors, for inlet and outlet, were used. Existing relay drivers (designated V32 to 35) were used to actuate the motors through an actuator relay assembly. Four drivers were required to implement direction reversal (open and close) of the motors.

C/M I Software

Several of the software routines of the ARX-1 C.M I software were modified in order: (1) to increase reliability, (2) to incorporate permanently changes that had been made to the software during prior programs and (3) to add new capability. Appendix 1 is a listing of the ARX-1 software modules and gives a summary of those that were modified.

In addition, one new software module (named CYCLIC) was created. This module provided for alternating between "normal" and "standby" modes representative

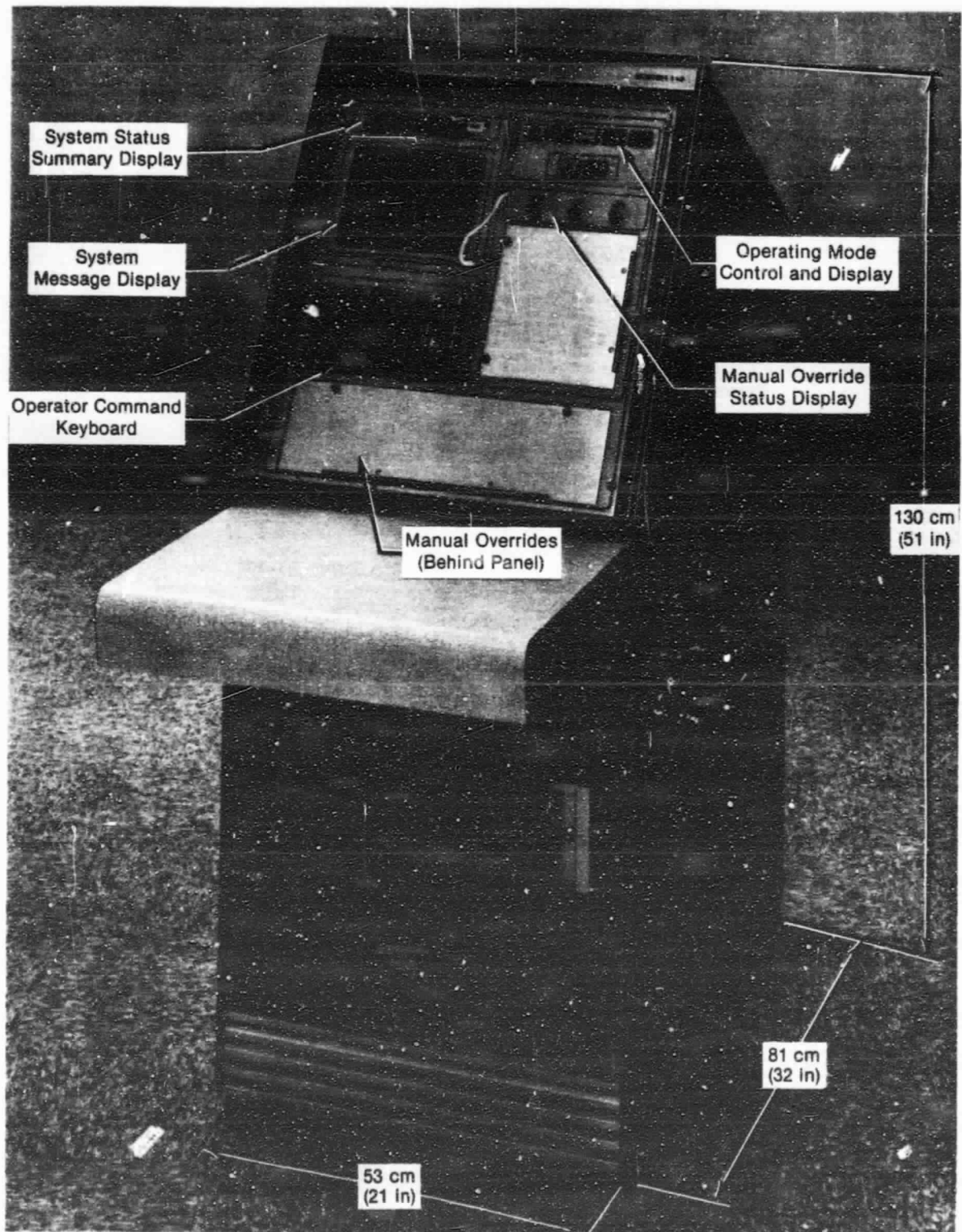


FIGURE 10 ARX-1 C/M I

TABLE 5 ARX-1 PHYSICAL CHARACTERISTICS SUMMARY

<u>Characteristic</u>	<u>M/E A</u>	<u>C/M I</u>
Weight, kg (lb)	144 (316)	118 (260)
Size, cm (in)		
Height	117 (46)	155 (61)
Width	76 (30)	53 (21)
Depth	102 (40)	81 (32)
Volume, m ³ (ft ³)	0.91 (32)	0.57 (20)
Power, W	800	525

TABLE 6 ARX-1 C/M I HARDWARE MODIFICATIONS

- Replaced A/D and A/D Expander Boards with two upgraded A/D Boards.
- Installed SFWEM current shutdown relay.
- Replaced failed amplifier on signal conditioning Card G for T016.
- Replaced failed thermal reference junction for T016.
- Replaced two pulse width modulation (PWM) chips on EDCM/SFWEM current controller.
- Changed signal conditioning to accommodate 3-FPC pressure signals (P010, P013, P014).
- Added wiring to interface DARS with C/M I (for cell voltages) and with TSA Parametric Data Display (for temperatures, pressure, flows).
- Replaced failed pressure sensor (P013) and modified signal conditioning to increase gain.
- Replaced failed panel meter (in TSA) for SFWEM cell voltage.

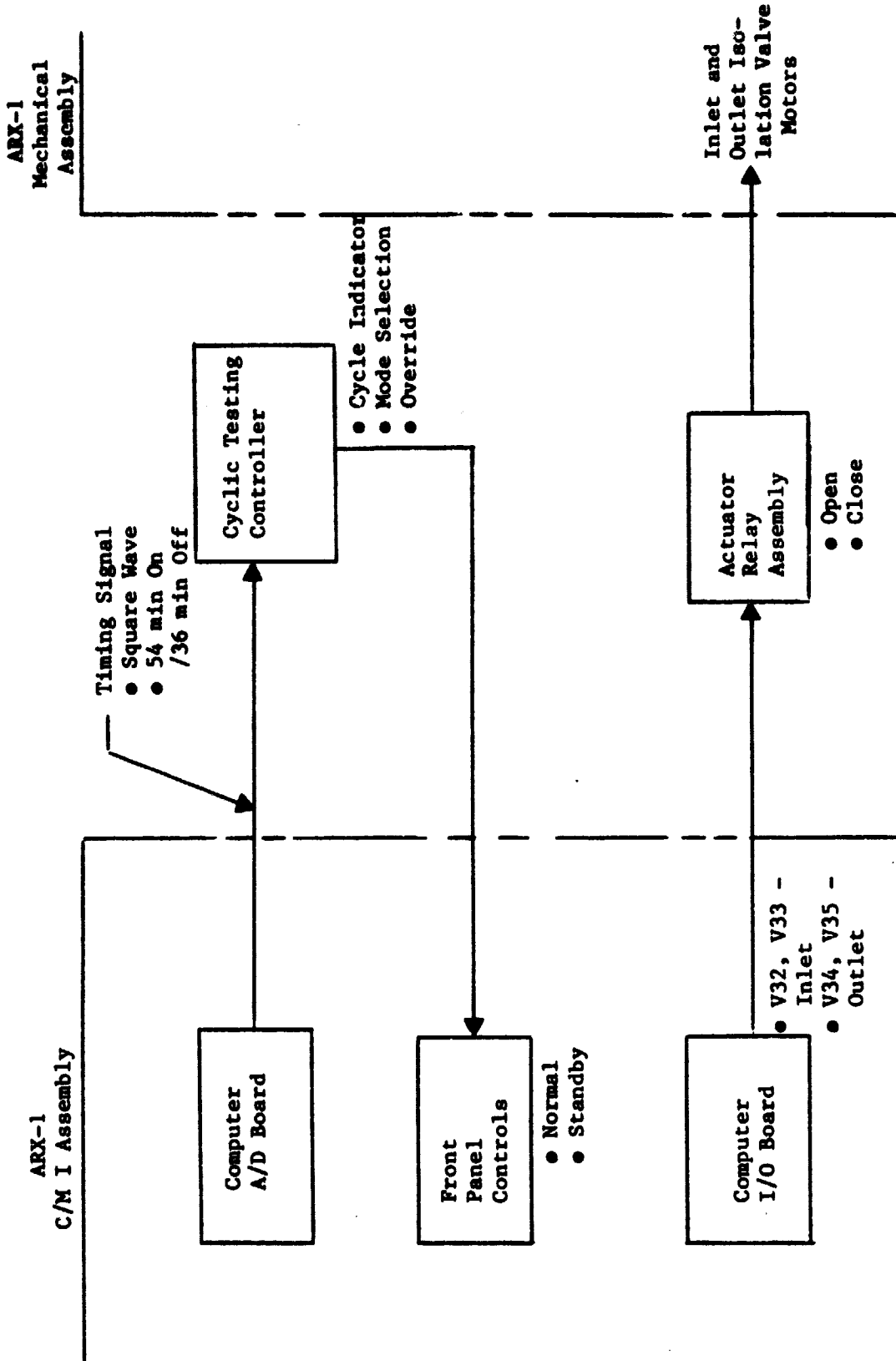


FIGURE 11 BLOCK DIAGRAM OF CYCLIC TESTING IMPLEMENTATION

of the 56/34 min light/dark cycle operation. Although this module runs continuously, it is only enabled when a hardware switch is activated. Generally, the ARX-1 was transitioned from unpowered mode to shutdown and then transitioned to normal. After observing the performance over some length of time, cyclic operation was then selected. Transitions between normal and standby were then automatically initiated. The actual transitions are given in Appendix 2.

TEST SUPPORT ACCESSORIES DEVELOPMENT

The existing TSA of the ARX-1 were refurbished, modified or upgraded to accommodate the testing objectives of the program. Additional capability was added to facilitate the specific testing that was required by the program. A block diagram of the total TSA supporting testing of the one person ARS with its C/M I is shown in Figure 12. Some of the TSA hardware was developed as part of this program. Other hardware was provided from prior programs and modified. The hardware identified as "N₂H₄ refill and supply" remained intact during the test program but was not used. The high N₂ pressure supply, coolant supply unit, water source, vent/vacuum source, fluids supply unit, air supply unit and its control, DC power supply unit and parametric data display remained as previously developed or had slight modifications. New or additional capability included the pCO₂ and dew point controls and the DARS. The following subsections describe the key components of the ARX-1 TSA with emphasis on those that were upgraded or developed.

Air Supply

The Air Supply Unit (ASU) for the ARX-1 is a closed loop air conditioning system designed to simulate the various air temperature, gas composition and humidity conditions projected to be encountered in a spacecraft cabin. The ASU was used to supply process air to the ARX-1. It also interfaces with the fluids supply unit and, with the controls described below, was used to establish the process air conditions required for the program's testing.

The principal components of the ASU are pictured in Figure 13. Its design specifications are listed in Table 7. Air flow is established by a constant speed blower and the settings for the flow control valves. While the total circulation can be up to 17 m³/min (600 ft³/min), it is possible to draw off a desired quantity of process air. For the ARX-1, this was 2.8 m³/min (100 ft³/min).

Aside from the sensors, all instrumentation is housed in the ASU control/monitor cabinet pictured in Figure 14. This unit includes the controls to operate the blower, water pump and heater; the instrumentation and sensors to monitor and control temperature, pressure, humidity, CO₂ and O₂ levels and the capability to calibrate the instruments. In addition, shutdown capability both within the ASU and to and from the ARX-1 exists. The shutdown parameters are dry bulb and dew point temperature, air flow, H₂ concentration and an externally generated signal from the ARX-1. During the testing, this signal indicates shutdown whenever the ARX-1 was not in "normal." There is also a

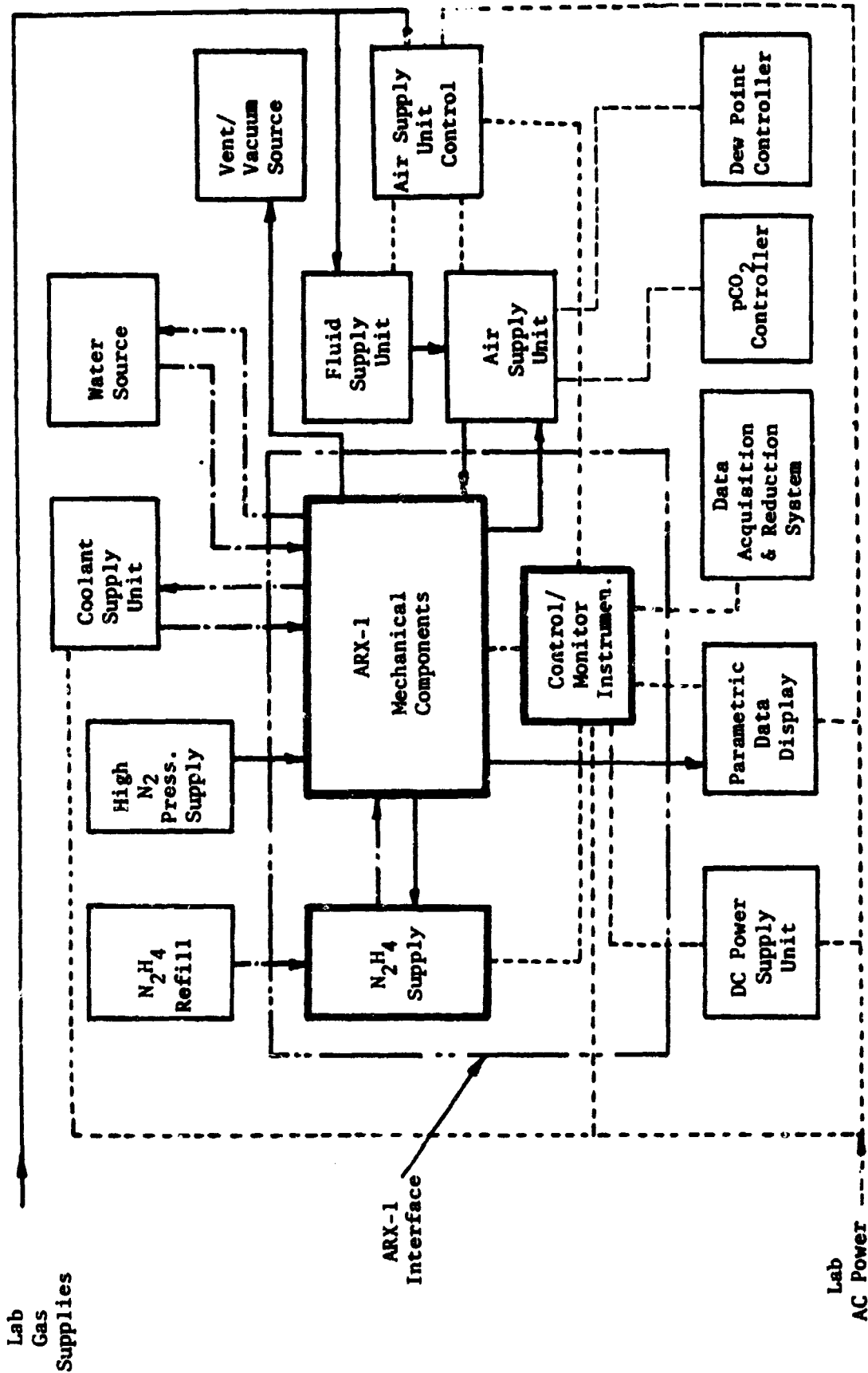


FIGURE 12 TSA BLOCK DIAGRAM

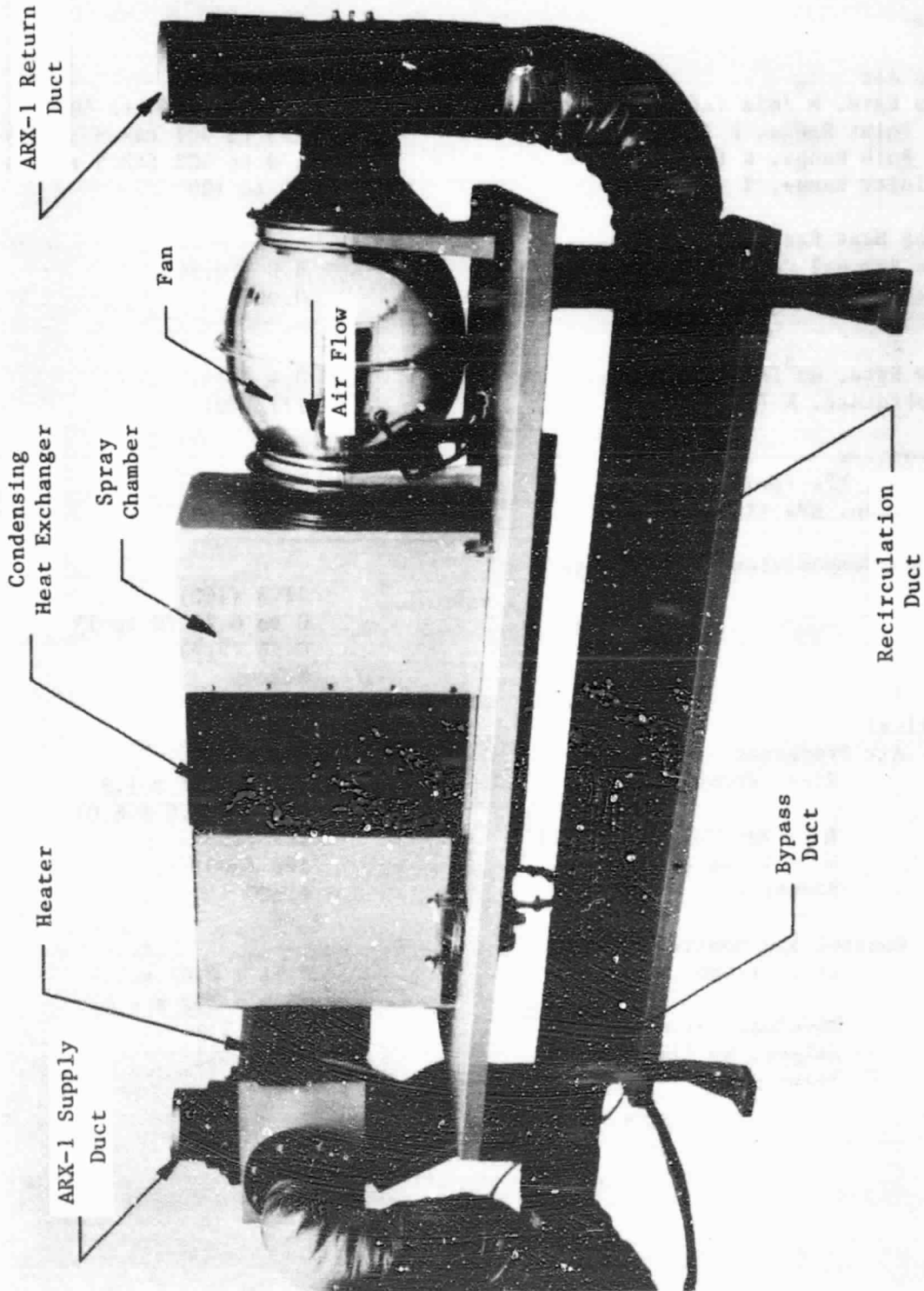


FIGURE 13 AIR SUPPLY UNIT

TABLE 7 ASU DESIGN SPECIFICATIONS

Crew Size	6 Max.
Processed Air	
Flow Rate, m ³ /min (cfm)	0 to 17.0 (0 to 600)
Dew Point Range, K (F)	279 to 301 (42.5 to 82)
Dry Bulb Range, K (F)	279 to 302 (42.5 to 85)
Humidity Range, %	26 to 100
Condensing Heat Exchanger	
Heat Removal Capacity, kJ/s (Btu/h)	6.0 (20,500)
Effectiveness	0.905
Coolant	
Flow Rate, dm ³ /s (gpm)	0.4 (6)
Temperature, K (F)	277 (40)
System Pressure	
Nominal, kPa (psia)	101 (14.7)
Deviation, kPa (in H ₂ O)	±0.74 (±3)
Nominal Gas Composition, kPa (mm Hg)	
O ₂	21.3 (160)
CO ₂	0 to 0.93 (0 to 7)
H ₂ O	0.76 (5.7)
N ₂	Makeup
Physical	
Air Processor	
Size, WxDxH, m (ft)	3.4 x 0.91 x 1.8 (11.0 x 3.0 x 6.0)
Envelope Volume, m ³ (ft ³)	5.7 (200)
Weight, kg (lb)	270 (600)
Power, W	6,500
Control and Monitor Cabinet	
Size, WxDxH, m (ft)	0.55 x 0.67 x 1.8 (1.8 x 2.2 x 6.0)
Envelope Volume, m ³ (ft ³)	0.65 (23)
Weight, kg (lb)	114 (250)
Power, W	1,000

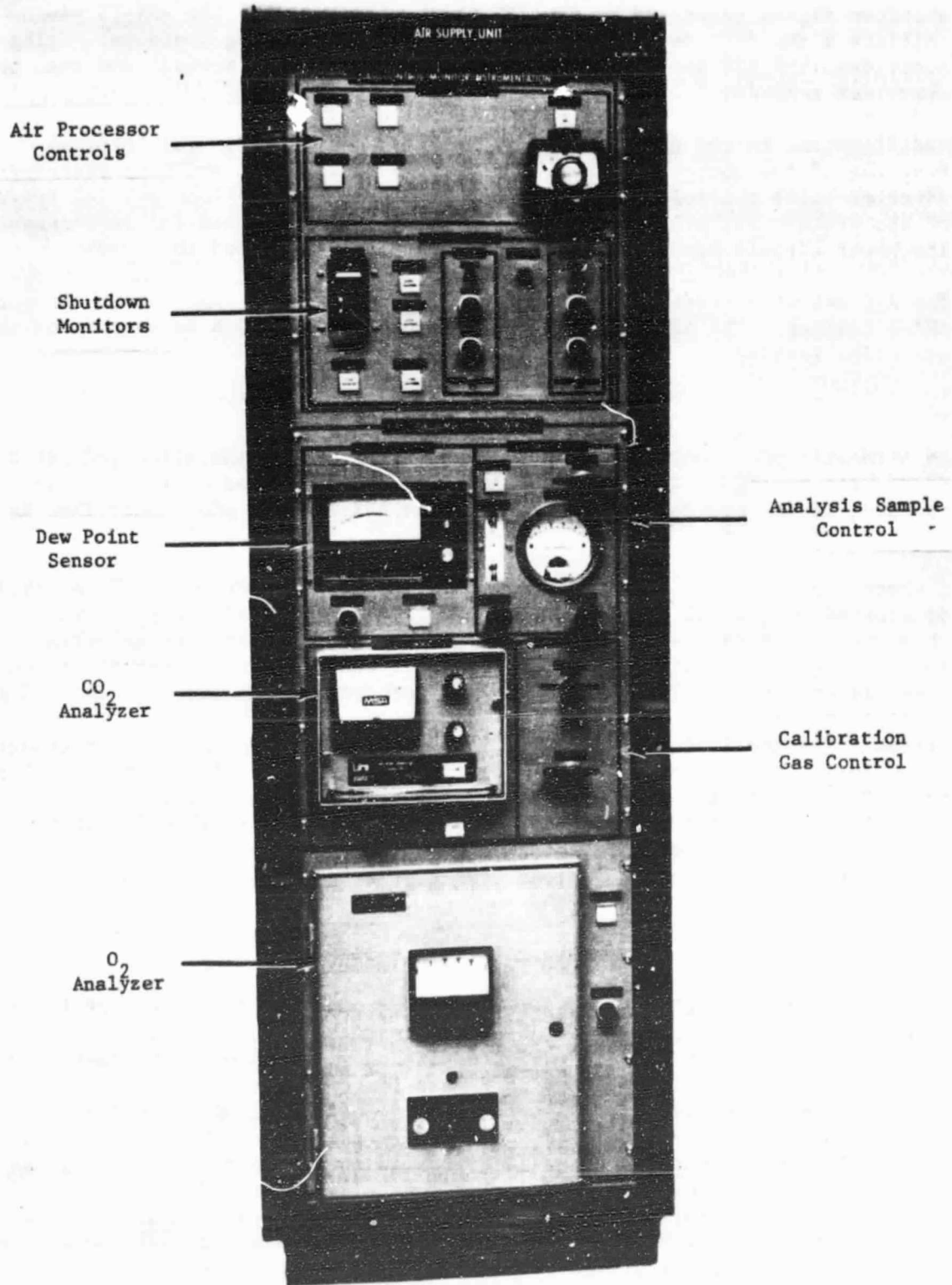


FIGURE 14 ASU CONTROL AND MONITOR INSTRUMENTATION

shutdown signal generated by the ASU which, if sensed by the ARX-1, would initiate a shutdown sequence in response to the ASU being shutdown. Using overrides, the ASU and the ARX-1 can be established in "Normal" and then the overrides removed.

Modifications to the ASU made under the program included: (a) internal rewiring of the control cabinet, (b) removal of the $p\text{CO}_2$ and heat exchanger diverter valve controls for installation in their own enclosures, (c) rewiring of the process air heater for greater temperature range and (d) replacement of its power circuit breakers/relays which marginally handled the loads.

The ASU met or exceeded all of its design specifications throughout the entire ARX-1 testing. The ASU has operated in excess of 15,000 h in support of this and prior testing.

$p\text{CO}_2$ Controller

An automatic $p\text{CO}_2$ controller was designed, fabricated, installed and interfaced with the ASU. This unit permitted automatic reproducible variations of the $p\text{CO}_2$ of the process air supplied to the ARX-1. The $p\text{CO}_2$ controller is shown in Figure 15.

A block diagram of the $p\text{CO}_2$ controller is shown in Figure 16. A 24-hr cycle of desired $p\text{CO}_2$ level is stored in a programmable read only memory (PROM). This cycle corresponds to a typical crew work/sleep cycle. At selected intervals (approximately 5.6 min) a clock increments the counter and a new level is outputted. The output value is compared to a measured value and a series of three solenoid valves introduce more or less CO_2 into the ASU air stream. The amplitude of the resulting profile will depend on the settings of the valves. A range of 0-5 mm Hg $p\text{CO}_2$ can be achieved. During the testing of the ARX-1 the profile shown in Figure 17 was used. The $p\text{CO}_2$ controller also had a front panel switch which permitted manual operation in which case a desired level could be achieved through a dial potentiometer setting. This capability was used during periods when a constant $p\text{CO}_2$ to the ARX-1 was desired.

Dew Point Controller

During periods of high crew activity both the $p\text{CO}_2$ and dew point (or relative humidity) of a spacecraft cabin will increase. The capability to simulate this behavior in the ASU was accomplished with a dew point controller. This dew point controller, shown in Figure 18, operated in a similar manner as the $p\text{CO}_2$ controller described above. It also had an automatic and manual mode. During the manual mode the desired dew point could be selected and fixed. In the automatic mode, a 24-h profile for spacecraft dew point was generated. The output of the dew point controller operated a diverter valve which set the temperature of the coolant passing through the ASU heat exchanger. The air outlet of the heat exchanger is nearly saturated at 100% humidity and therefore the dew point of the process air is very near the coolant temperature in the heat exchanger. The dew point levels were varied from 281 K (47 F) to 294 K (65 F) in a 24-h profile which was assumed similar to the $p\text{CO}_2$ profile.

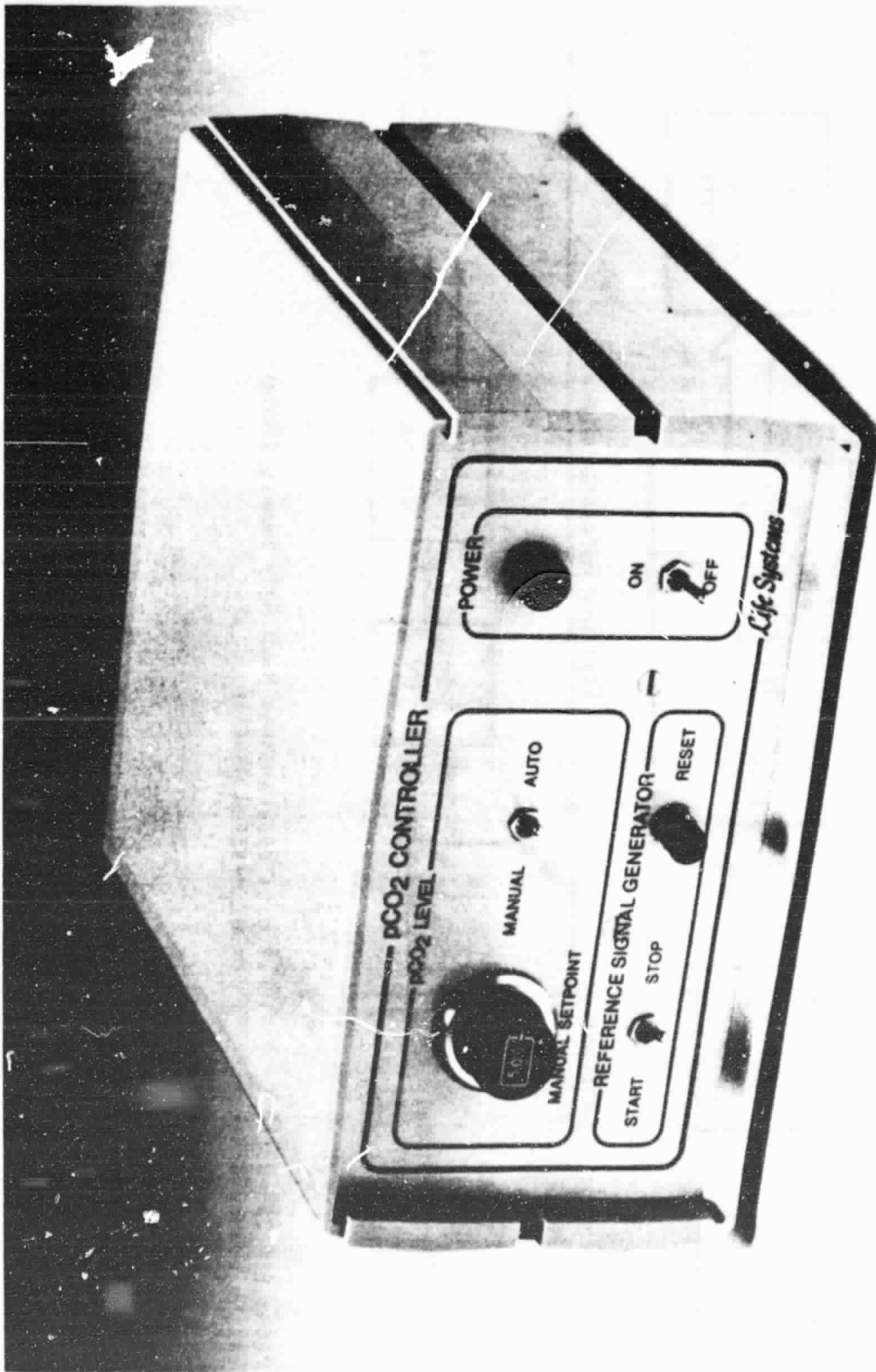
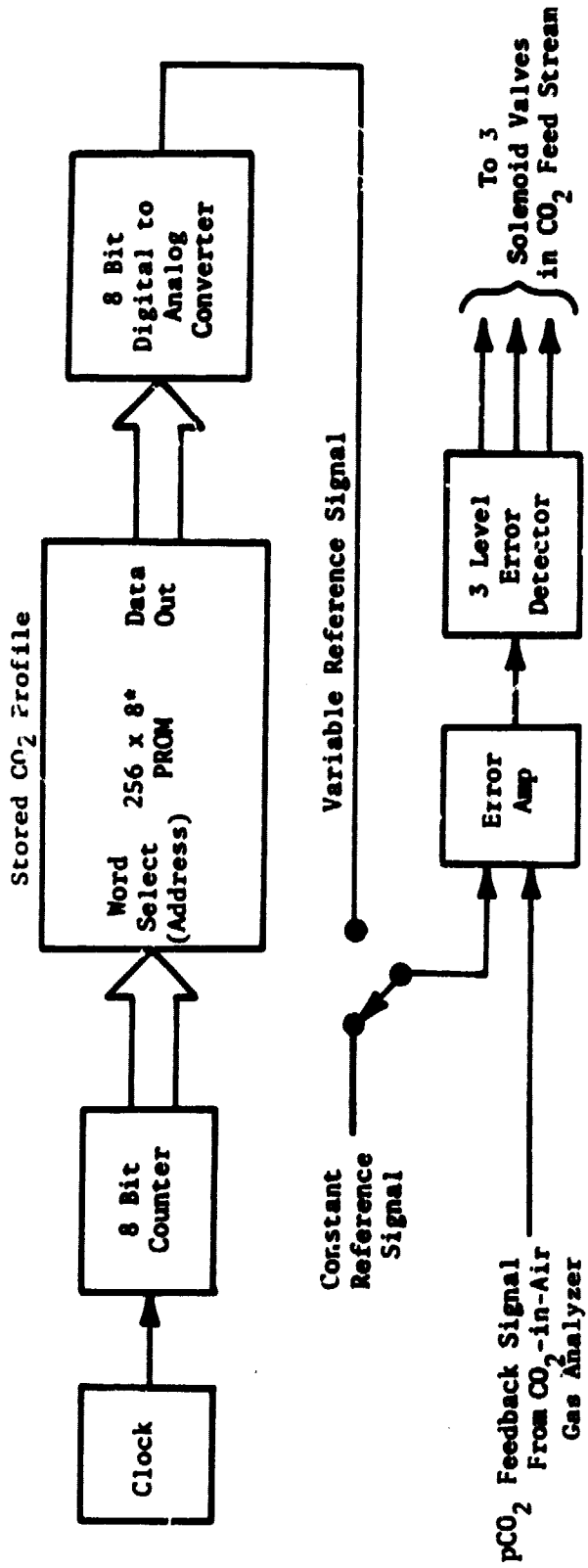


FIGURE 15 pCO₂ CONTROLLER



*256 x 8 = 256 words each with 8 bits Programmable Read Only Memory (PROM) can be erased and reprogrammed for desired profile

FIGURE 16 BLOCK DIAGRAM, VARIABLE pCO₂ CONTROLLER ELECTRONICS

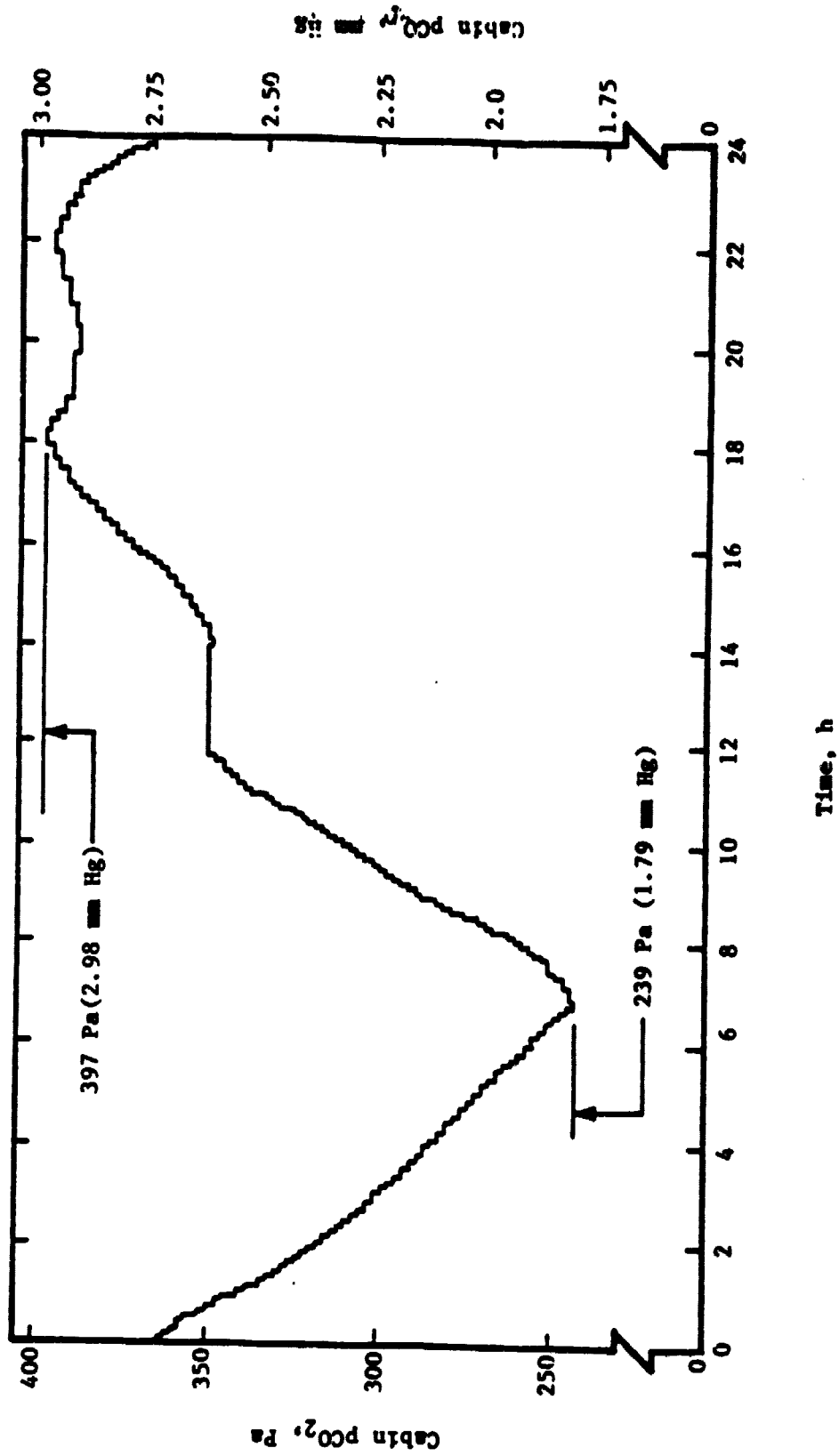


FIGURE 17 SIMULATED CABIN pCO₂ PROFILE USING pCO₂ CONTROLLER

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OF POOR QUALITY

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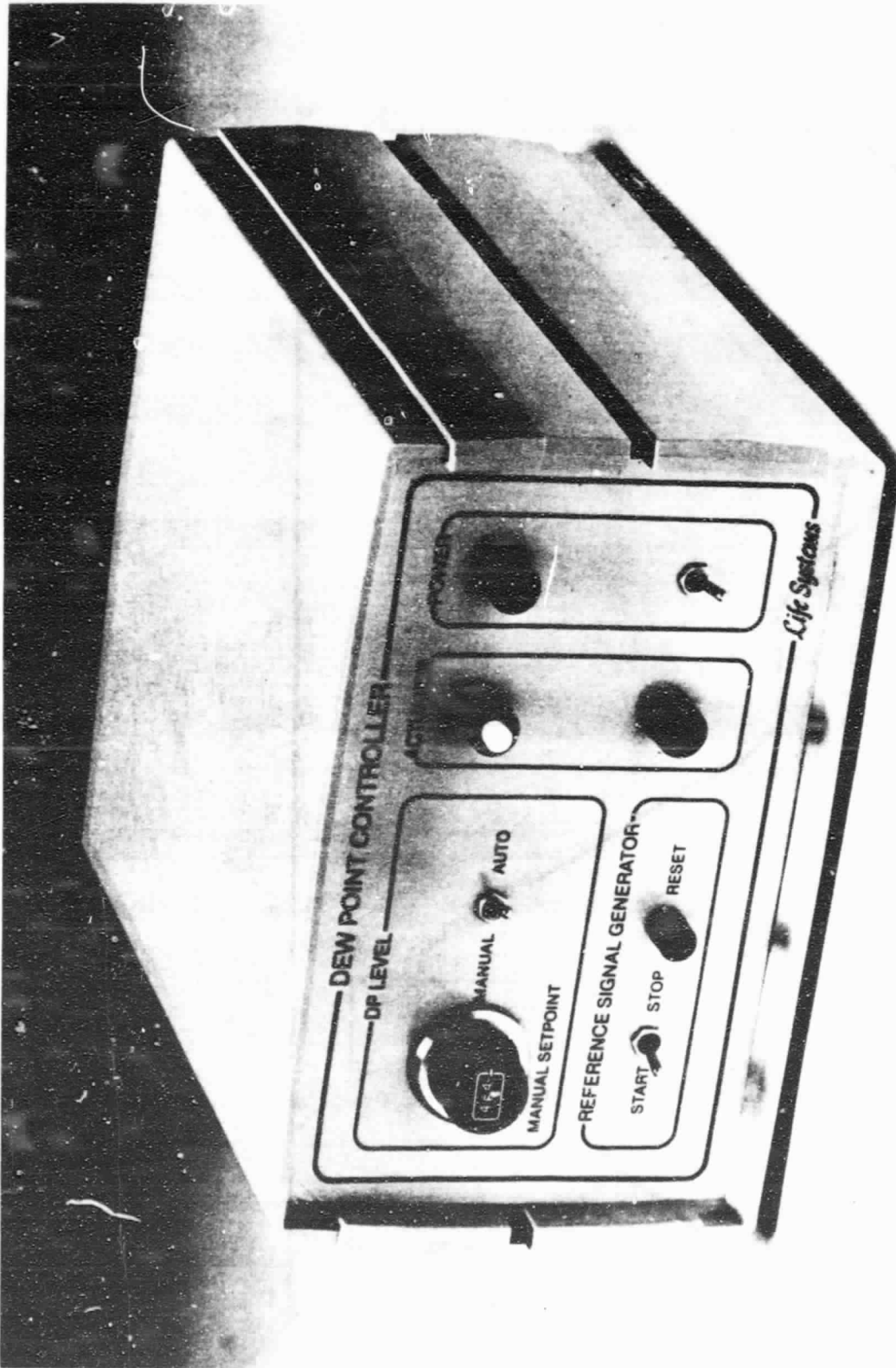


FIGURE 18 DEW POINT CONTROLLER

Coolant Control

Variations in spacecraft coolant are normally expected to change on an orbital basis as opposed to being related to crew activity or function. Specifically, for a low earth orbiting spacecraft the alternating lightside/darkside exposure to the sun will impact the spacecraft heat exchanger, change the heat loads and vary the heat rejection capacity of the spacecraft coolant. Therefore, simulations of coolant changes were accomplished by changing the temperature of the coolant source supplied to the ARX-1 (and its various components) on a 96 min basis. The coolant temperatures ranged from 280 K (44 F) for the darkside to 290 K (62 F) for the lightside.

Data Acquisition and Reduction System

The capability for automatic, unattended data collection during testing was incorporated into the existing ARX-1 system. A block diagram of the arrangement is shown in Figure 19. The added component is the DARS which is shown in Figure 20. This unit permitted automatic recording of ARX-1 parameters at a predetermined frequency, typically every five minutes. A total of 31 analog signals were connected from the existing TSA parametric data display to the DARS. These included all cell voltages and key temperatures, pressures and flows (see Table 8). The DARS was shared in the laboratory with another subsystem under test and as such was not dedicated solely to the ARX-1. However, a scheme for time sharing its usage was implemented.

SYSTEM TESTING

Testing of the ARX-1 was conducted in two main categories - continuous and cyclic operation. Under the continuous operation various parametric testing was also accomplished. An overview of the testing that was accomplished under the subject program is shown in Table 9. Shown is the testing broken into the two main categories, the types of test and the duration of each test.

A total of 1,350 h of testing (56 d) was accumulated during the program. These hours refer to the system operating as a total integrated unit with all components operating after a successful one-button automatic startup. This means operation in the Normal mode and excludes the time required for the transitions Shutdown to Normal and Normal to Shutdown. These transitions typically require 0.5 h each and primarily involve the pressurization and depressurization of the Static Feed Water Electrolysis Module (SFWEM). To this should be added approximately 500 h of prior integrated operation for total integrated operation of the ARX-1 since its fabrication was completed of almost 2,000 h. This indeed is a remarkable record for this system.

The following two sections discuss the parametric and cyclic testing results. These are followed by observations made on the overall ARX-1 development program including experiences gained.

Parametric Testing

A total of 976 h of integrated operation in the Normal mode was achieved during the parametric testing of the system.

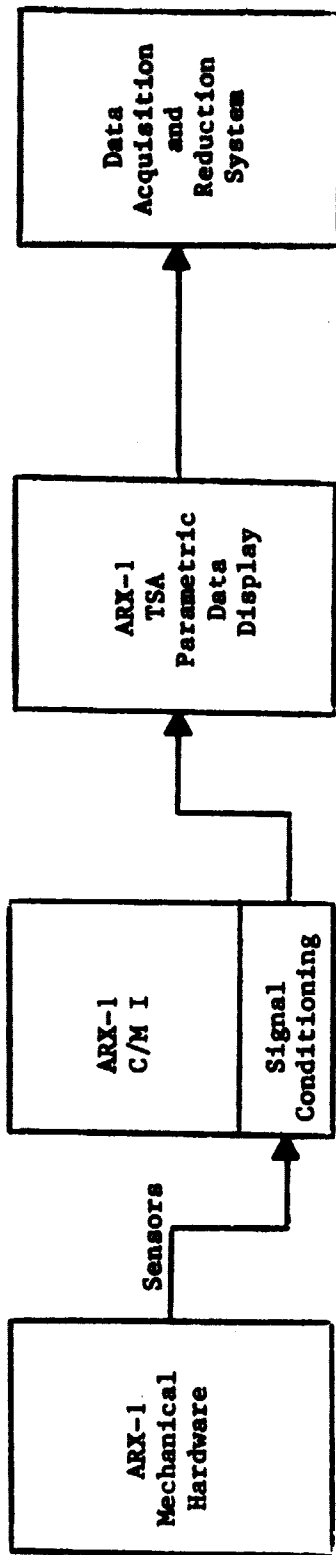


FIGURE 19 AUTOMATIC DATA ACQUISITION BLOCK DIAGRAM

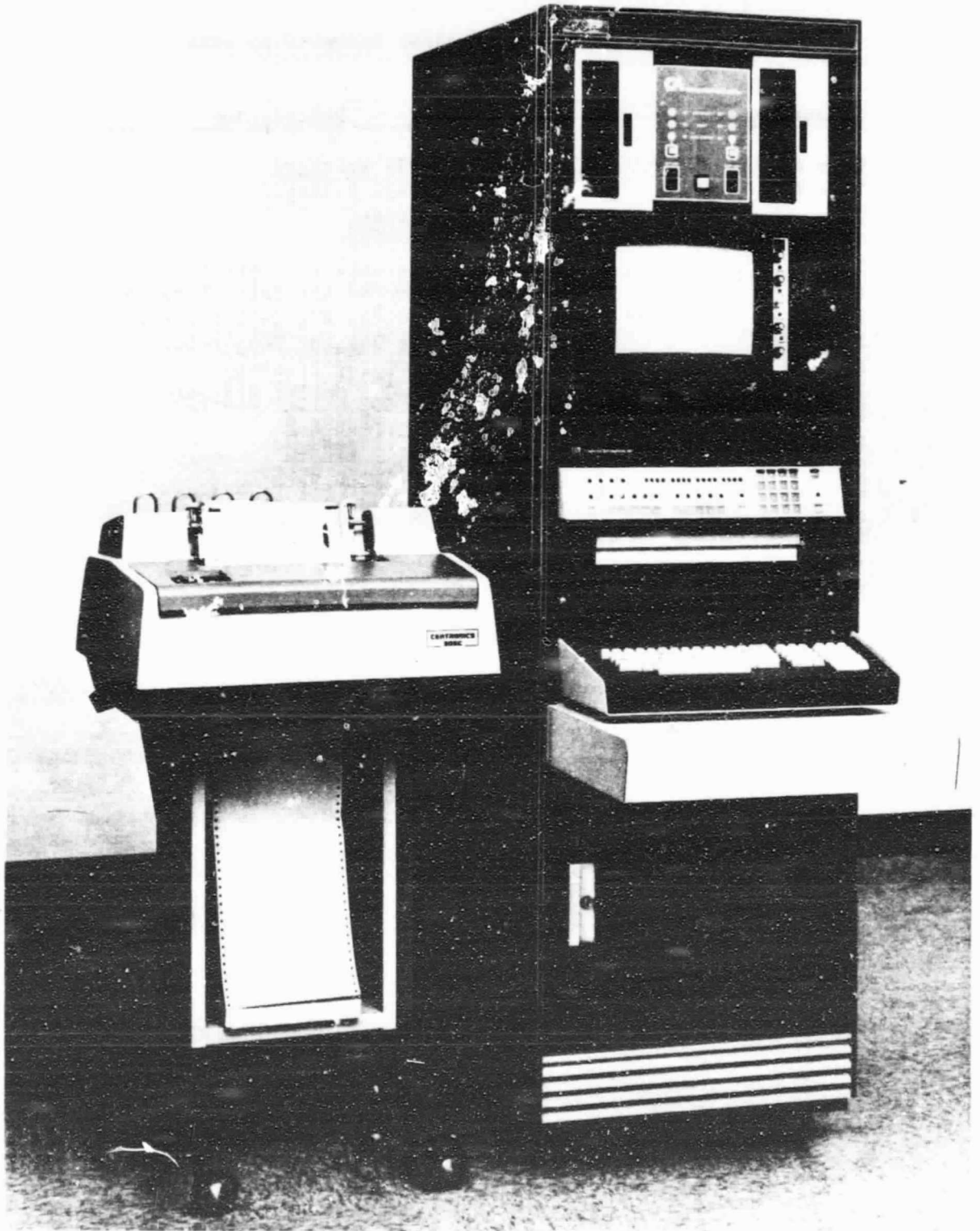


FIGURE 20 DATA ACQUISITION AND REDUCTION SYSTEM

TABLE 8 ARX-1 PARAMETERS RECORDED BY DARS

<u>Sensor Code</u>	<u>No.</u>	<u>Description</u>
E1 - E6	6	EDCM Cell Voltages
E7 - E18	12	SPWEM Cell Voltages
I1	1	EDCM Current
I2	1	SPWEM Current
T4	1	CHCS Air Outlet Temperature
T8	1	EDCM Process Air Inlet Temperature
T11	1	EDCM Process Air Outlet Temperature
T14	1	Sabatier Reactor Temperature
P1	1	EDCM H ₂ Inlet Pressure
P2	1	EDCM H ₂ /CO ₂ Outlet Pressure
P11	1	SPWEM O ₂ Pressure
P12	1	SPWEM H ₂ Pressure
Q1	1	CHCS Air Flow Rate
Q2	1	EDCM Process Air Flow Rate
Q3	1	SPWEM H ₂ Flow Rate
	<u>31</u>	

TABLE 9 ARX-1 TESTING OVERVIEW

Description	Duration, h ^(a)	
	Per Test	Cumulative
A. Parametric		
Checkout	9.8	9.8
Normal	118.5	128.3
Variable pCO ₂	387.5	515.8
Variable Dew Point Temperature	196	711.8
Variable Coolant Temperature	264	975.8
B. Cyclic		
Checkout	36	1011.8
Cyclic	342.4 ^(b)	1354.2

(a) Operation in Normal mode, or in the case of Cyclic Testing, Normal and Standby.

(b) Total of 206 cycles each of 54 min light/36 min dark duration.

Figures 21 through 25 show the overall system and subsystem performances throughout the parametric testing period. Generally, data points were taken on a daily basis. For those parametric tests which incurred variation on a much larger frequency, say a complete cycle per 24 h, separate data was taken to monitor those components whose performances were impacted by this mode of operation. These figures indicate overall performance based on the data points which show the system status "snapshot" taken at the times shown. Therefore, the curves include all of the continuous operation data including checkout, normal operation and the three parametric tests. They will be discussed first.

The overall system performance is shown in Figure 21. It is seen that the ARX-1 removed CO_2 near the one-person level and generated O_2 above the design level. The less than one-person CO_2 removal performance is discussed below. The net O_2 generated is the O_2 generated by the SFWEM less that required for the CO_2 removal function. The curve for net water recovered is the algebraic total of the water that is (1) removed by the CHCS from the simulated cabin atmosphere, (2) removed by the S-CRS condenser/separator and (3) supplied to the SFWEM. Since the first factor is dependent on the dew point of the process air into CHCS and the temperature of the coolant to the heat exchanger, that number can sometimes be small and, in fact, zero. Therefore, the net water recovered may be negative for certain data points reflecting real world operation.

While Figure 21 presents the performance of the overall ARX-1 system, individual subsystem performances for the SFWEM, EDCM, S-CRS, CHCS are given in Figures 22 through 25, respectively. The SFWEM (Figure 22) operated near its nominal design point temperature of 339 K (150 F) except for a 200 h period, as indicated, during which it operated at 355 K (180 F). It was during this period that the subsystem experienced a loss of coolant and the SFWEM was allowed to reach an equilibrium temperature of 355 K (180 F). As expected, the average cell voltage, and hence power consumption, decreased approximately 5.4 mV/K (3 mV/F) 22 W during this period, which was expected.

The EDCM performance shown in Figure 23 illustrated good cell voltage but slightly less CO_2 removal rate than design (1.0 kg/d). This was attributed to the poor performance of one of the cells specifically, Cell No. 6. It was found during the testing that the module was suffering electrolyte imbalance due to air flow maldistributions. The maldistributions were a direct effect of the physical construction of the inlet and outlet ducts. During the testing this condition was rectified by added turning vanes in the inlet and outlet manifolds. These steps corrected the air flow distribution through Cell No. 6, but did not permit full recovery to design operations. The module was recharged prior to the cyclic testing which restored its performance.

The Sabatier reactor performance data of Figure 24 shows variations of H_2 and CO_2 conversion efficiency from 32% to 74% and 64% to 114%. It should be noted that these data are calculated from three measured parameters - inlet CO_2 concentration, inlet H_2/CO_2 flow rate and outlet flow rate - through a set of equations. These equations are sensitive to the measured parameters and in some cases can yield efficiencies greater than 100%. The CO_2 conversion

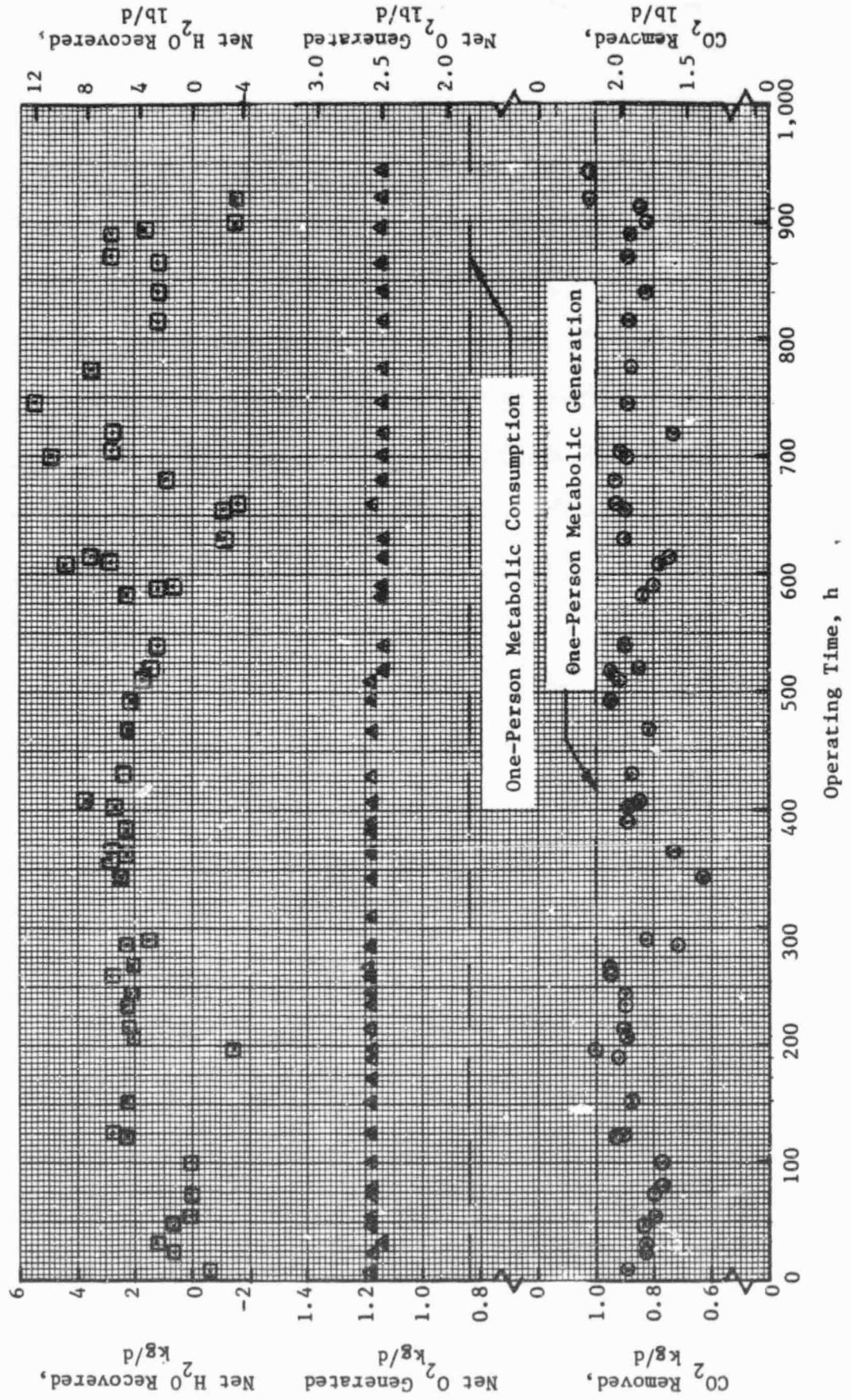


FIGURE 21 SYSTEM PERFORMANCE

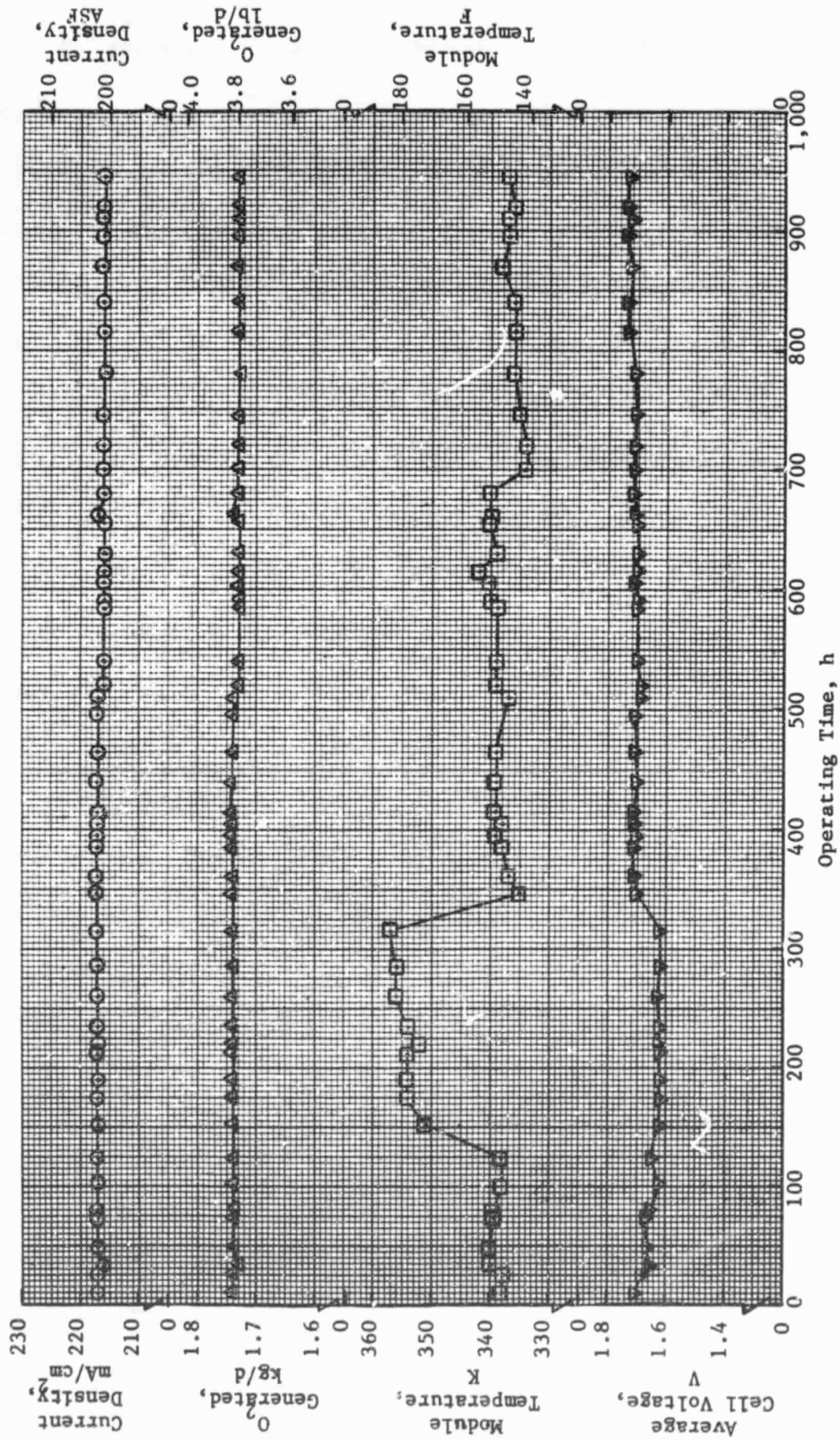


FIGURE 22 SFWM PERFORMANCE.

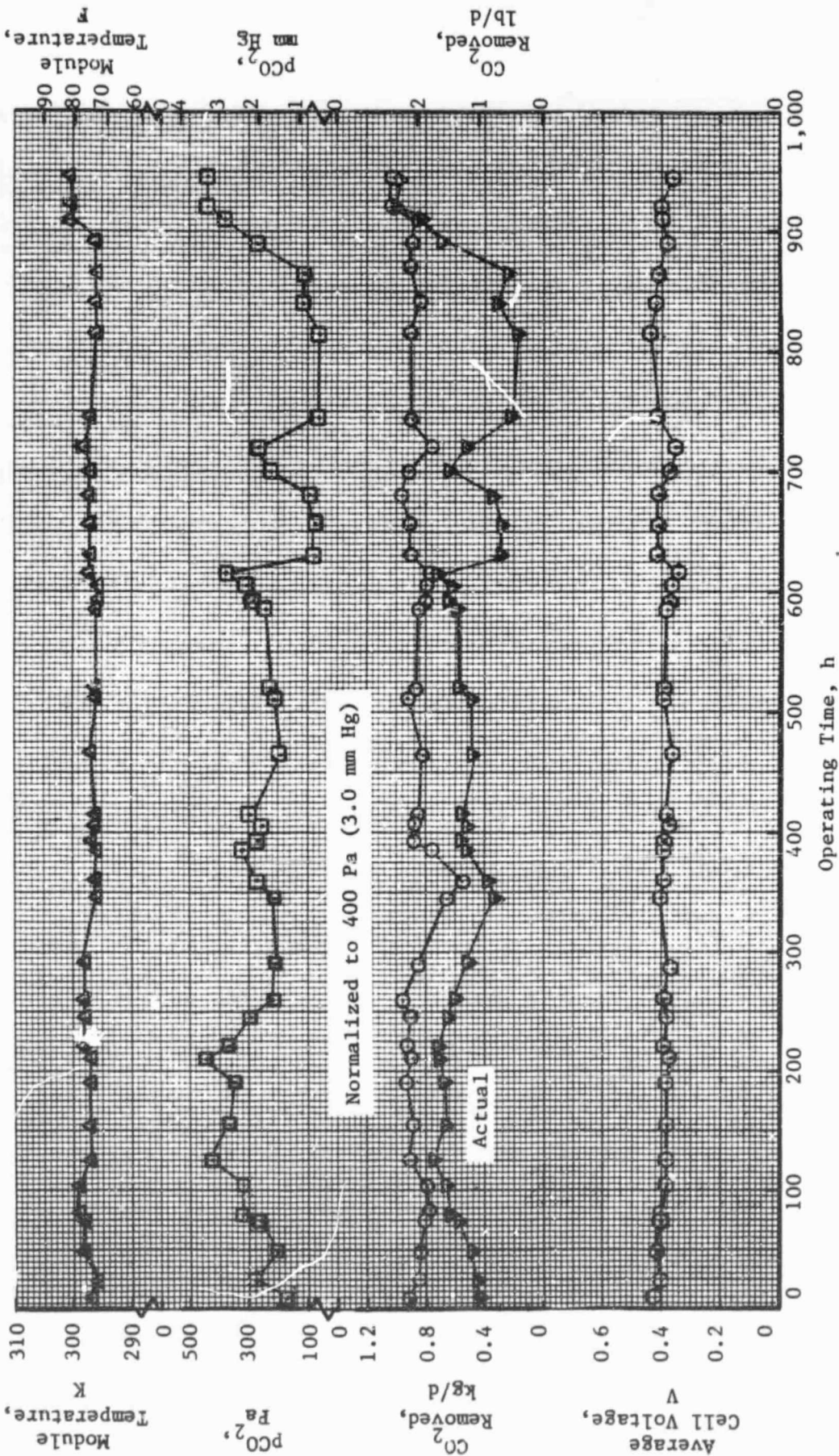


FIGURE 23 EDM PERFORMANCE

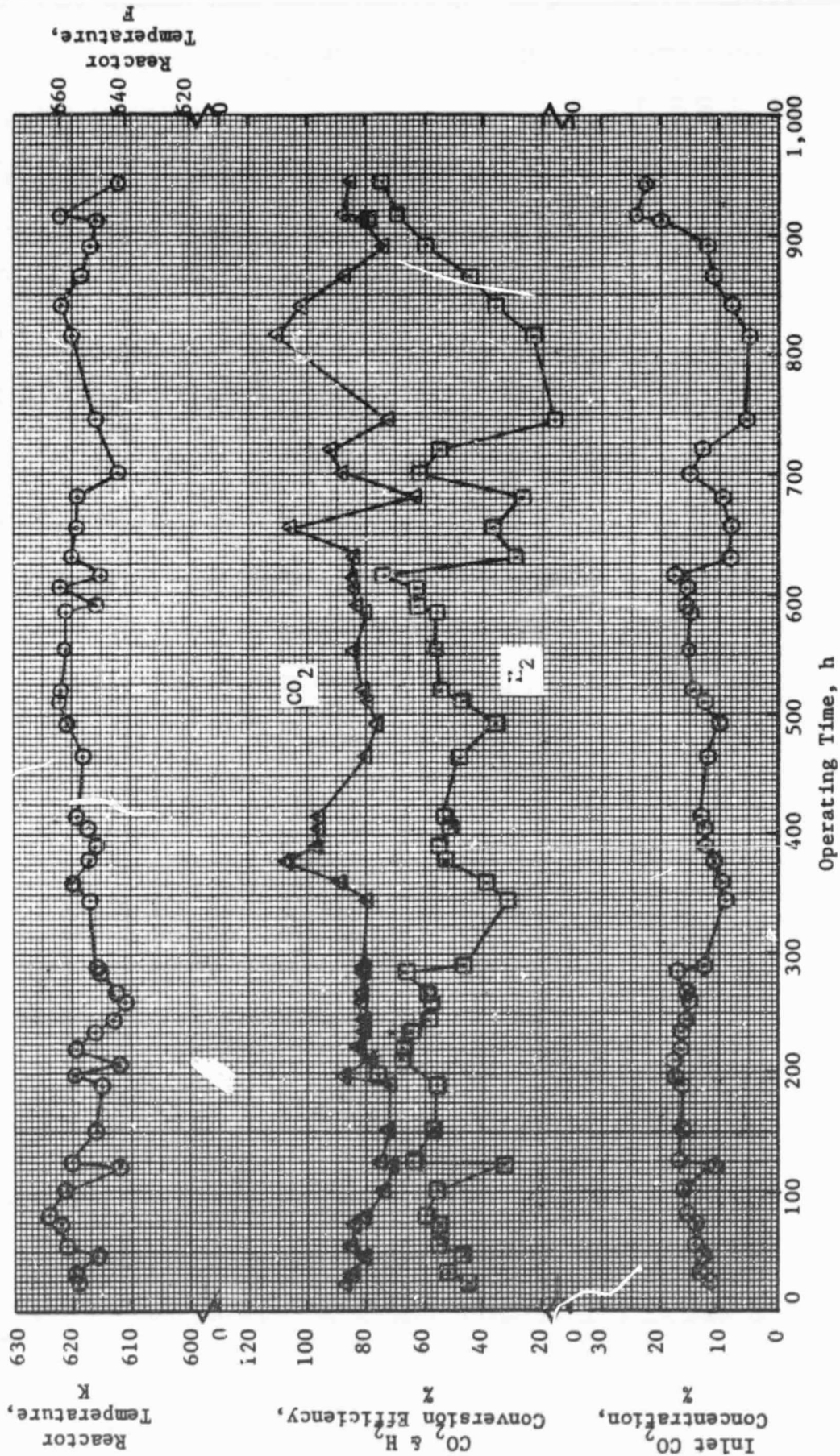


FIGURE 24 SABATIER REACTOR PERFORMANCE

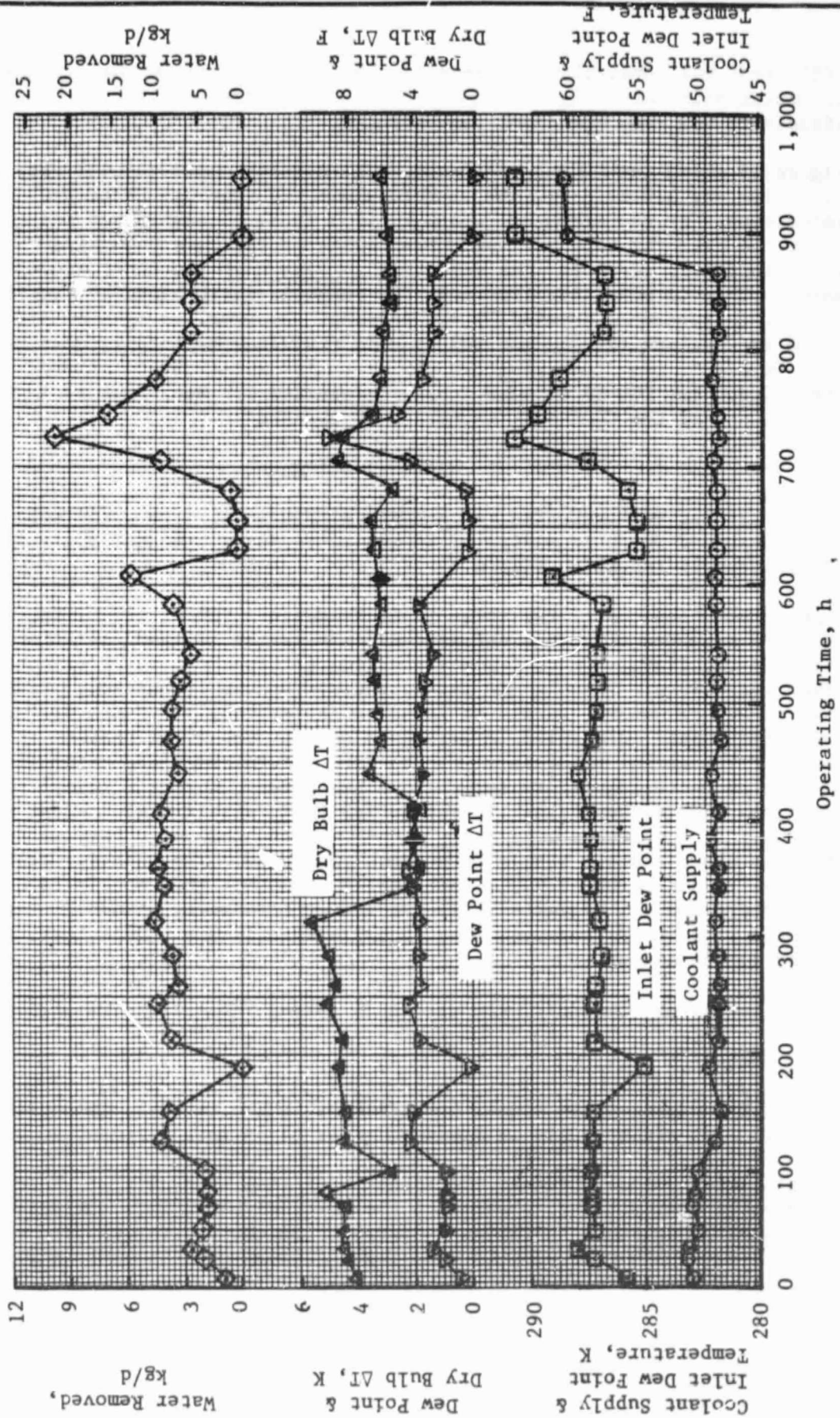


FIGURE 25 CHCS PERFORMANCE

efficiency was generally between 80 and 90 percent. Since the testing was conducted with excess H_2 (to ensure high CO_2 conversion), the H_2 conversion efficiency was less than 100%, as expected.

Figure 25 shows the CHCS performance. The average water removal rate was approximately 3.0 kg/d (6.6 lb/d) throughout the testing. When the requirement for the SFWEM of 1.95 kg/d (4.3 lb/d) is subtracted and the water collected from the Sabatier condenser/separator (average 0.48 kg/d (1.06 lb/d)) is added to this value, it is seen that the ARX-1 accumulates water. This is generally true over the range of inlet humidity conditions and coolant temperatures covered by the testing. However, as seen in Figure 25, there are periods (at 650 and 900 h) when the water removed is near zero. This is due in the first case (at 650 h) to low inlet dew point and in the second case (at 900 h) to high coolant temperature. Both factors impact performance of the CHCS heat exchanger as expected.

Cyclic Testing

Cyclic testing was conducted for a total of 380 h (16 d) and included 206 cycles each of which consisted of 54 min rates Normal (light) operation and 36 min Standby (dark) operation.

Temperature behavior of the three major components (EDCM, SFWEM, Sabatier reactor) expected to change during cyclic operation is shown in Figure 26. Shown is the transition to Standby starting at time zero. The transition takes about 40 s. Then 40 min later, the system was transitioned to Normal. The Standby to Normal transition requires approximately 2.2 min during which the three events identified in Figure 26 occur. The SFWEM current is set to one half its normal value to allow the Three-Fluids Pressure Controller (3-FPC) pressure regulators (which have been frozen during Standby) to react. After one minute the current is set to its full value (19 A). After another minute, full current is applied to the EDCM. The component temperature profiles shown are the resulting dynamic responses. The Sabatier reactor response is due to the infusion of reactants and not the reactivation of its temperature control heater - it is not turned off during Standby. The drop was only 11 K (20 F) corresponding to approximately a 6 W heat loss, an insignificant amount.

The following observations were also made during the cyclic transitions:

SFWEM Operation

The SFWEM temperature in Normal operation was 339 K (150 F), and fell only 1.2 K (2.2 F) after 40 min in Standby. This is an insignificant amount.

In going from Standby back to the Normal operating mode, little effect on cell voltages was experienced compared to the prior normal value. This is primarily due to the temperature remaining essentially constant. The 12 cell voltages ranged from 1.63 V to 1.71 V in Normal and dropped to 1.29 to 1.35 V after 40 min in Standby and then returned to the previous range.

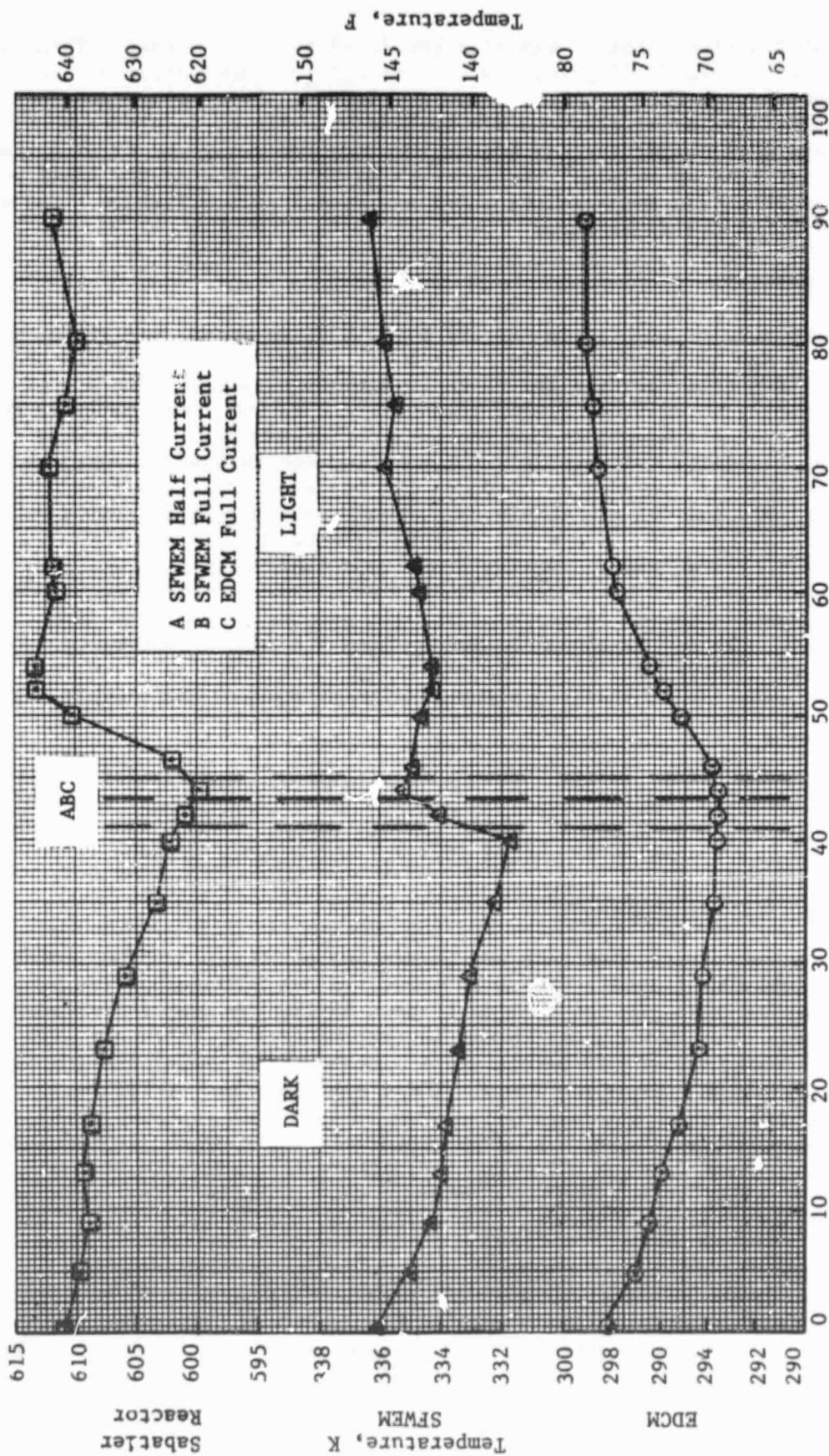


FIGURE 26 CYCLIC OPERATION TEMPERATURE PERFORMANCE

The 3-FPC H₂-to-system ΔP was 17.2 kPa (2.49 psid) in Normal. This fell to a low of 6.7 kPa (0.97 psid) due to some H₂/O₂ recombination but mostly leakage through the regulator which was frozen. This value rebounded to 15.0 kPa (2.18 psid) after 40 min in Standby. The O₂-to-system ΔP fell from 22.4 kPa (3.25 psid) to 14.5 kPa (2.10 psid) and recovered to 19.3 kPa (2.80 psid) after 40 min. The recovery of both is due to the small amount of N₂ available from purge valves which are opened during Standby. These drops in pressure were as expected.

EDCM Operation

The EDCM module temperature was 298 K (77.8 F) in normal operation, and fell after 40 min in Standby to 294 K (69.6 F). A key observation was the behavior of the EDCM cell voltages for 10 to 20 min after returning to Normal. This was directly correlated to EDCM temperature. It was found early in the testing that the module cooled too much during Standby. There were three reasons for this: (1) obviously, without current no heat is generated, (2) the bottom cells are physically close to the bypassed process air and are cooled convectively and (3) the module temperature control was initially disabled during Standby. The latter was done to prevent the coolant loop diverter valve from transgressing too far from its normal position. However, if some coolant is going to the liquid/liquid heat exchanger, which exchanges with the system coolant source this situation will eventually cool the module. Therefore, the software was changed to keep the module temperature control loop active during Standby. The resulting temperature drop was then only 24 K (4.3 F) over the first seven minutes which represents the thermal lag of the module.

The H₂ backpressure on the EDCM module controlled by a regulator downstream of the Sabatier reactor fell only 1.0 kPa (0.15 psid) from a value of 134 kPa (19.4 psia) after 40 min in Standby. This was an insignificant amount and demonstrates the value of having some N₂ purge during Standby.

Sabatier Reactor Operation

The Sabatier outlet flow rate and percentage of CO₂ in the EDCM anode exhaust were monitored. Figure 27 shows typical behavior of the Sabatier exhaust flow rate plotted from data taken during the transition from Standby to Normal. The curve shows three distinct regions of behavior: (1) an initial high peak (0 to 2 min), (2) a plateau (2 to 5 min) and (3) a decrease to about 600 cm³/min after 5 min. These are explained as follows:

1. During Standby the SFWEM purge valves are opened to maintain adequate flow to the 3-FPC for differential pressure control. The flow rate (less than 20 cm³/min) is that required to maintain gas pressure due to H₂ and O₂ recombination and leakage through the 3-FPC valve seats.
2. For the first 2 min of the transition from Standby to Normal the purge valves remain open. Also during this time the SFWEM is increasing current. The increased flow rate (to 2,000 cm³/min) is due to H₂ production of the SFWEM.

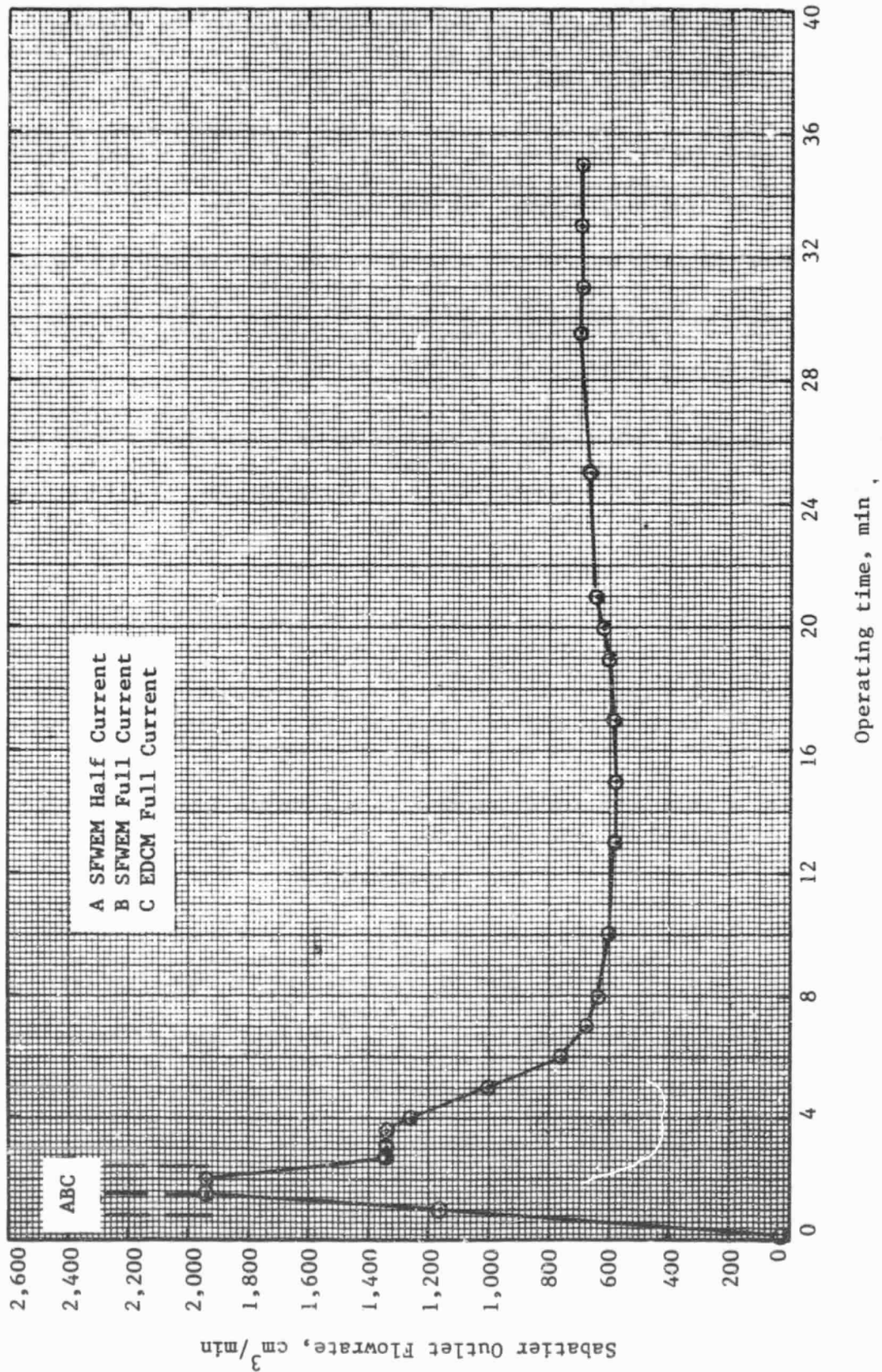


FIGURE 27 SABATIER OUTLET FLOWRATE AFTER TRANSITION FROM
DARK TO LIGHT

3. After 2 min the EDCM current control was enabled and the purge valves closed. It was at this time that the electrochemical reaction of the EDCM consumes H_2 and starts increasing the percentage of CO_2 in the anode exhaust gas through the Sabatier. The volumetric flow rate decreases.
4. From 2 to 4 min the Sabatier reactor is being flushed of residual gases by the reactants H_2 and CO_2 . This is the plateau region. The CO_2 mixture in the EDCM anode exhaust is increased to a stoichiometric mixture and the reaction starts.
5. As the reaction becomes more efficient, the volumetric (molar) reduction of four H_2 and one CO_2 molecules to one CH_4 molecule is seen. The gradual rise in flow rate after 20 min is probably due to the reactants mixture being further from stoichiometric for the particular data point that was recorded.

An important conclusion is that the reactor does not respond instantly to the entry of reactants even though the reactor is at temperature. Some flushing with reactants is required. It is assumed that a reactor sized for just one person (the ARX-1 reactor can handle up to three persons) would have less of a reaction startup delay, probably 1 or 2 min instead of the 6 min observed.

ECLSS AUTOMATED C/M I CONCEPTS

A key functional aspect of the future Space Station will be the use of advanced concepts for autonomous operation and independency of ground support personnel for day-to-day operation of the Space Station. New concepts of local and hierarchial control will be required. It was the purpose of a separate task of this program to look at the evolution of C/M I concepts in the context of totally automated control as applied to the ECLSS for Space Station.

The results of this task are documented in a separate report.⁽¹⁴⁾ The following summarizes the key findings.

C/M I Requirements

It is expected that the C/M I for the ECLSS will have over 70 control functions which the hardware and/or software must accommodate. They will emulate conventional hardware devices such as proportional, integral or differential (PID) controllers, adders, subtractors, dynamic lead-log compensators, etc. Table 10 identifies these functions. It is felt that some advanced functions (e.g., adaptive PID control, constraint polynomials, etc.) will only be possible because of the increasing capability of microcomputers. All of these functions must be accommodated by the C/M I. However, the decision as to where these functions will be accommodated will be determined by the architectural design of the entire Space Station C/M I structure. For example, signal conditioning and localized control of a subsystem would be appropriate to be handled by a subsystem controller. Data storage and retrieval would be more appropriately handled by a higher level, centralized, archival storage facility which would be shared among several systems. Table 11 shows some

TABLE 10 SPACE STATION C/M I CONTROL FUNCTIONS

A. INPUT CHARACTERIZATION

Analog Inputs
 Analog Input Conversion
 Transmitter Alarm Output
 Fall-Back Alarm Output
 Totalize Input
 T/C-RTD Input Conversion

Discrete Inputs
 Normal Contact Status
 Status Alarm Output

B. LOOP CONFIGURATION

Link Functions
 Load (specified signal)
 Char. Analog Input
 Temperature Comp. (Gas Measure)
 Input Signal Switch
 Character Discrete Input

PID Functions
 PID Basic Controller
 PID Ratio
 PID Auto-Ratio
 PID Auto-Bias
 PID Cascade
 PID Gap
 Adaptive PID Parameters
 Keyboard PID Parameters
 Manual Station
 External Output Tracking

Math Functions
 Multiply
 Divide
 Summation (Bias)
 Difference
 Square Root
 Square
 Absolute Value

Logarithm
 Exponential
 Polynomial
 Time Averaging

B. LOOP CONFIGURATION - continued

Limit Functions
 Low Select
 High Select
 Low Limit
 High Limit
 Constraint
 Transfer on Discrete
 Transfer on Analog Level

Dynamic Functions
 Lead/Lag
 Dead Time
 Velocity Limit
 Totalize

Special PID Functions
 PID Incremental

Batch Functions
 Transfer on Signal Value
 Time-based Signal Transfer
 Transfer on Discrete Status
 Time-based Discrete Transfer
 Unconditional Signal Transfer
 Mode-based Signal Transfer
 Mode-based Discrete Status

Logic Functions
 And
 Or
 Invert
 Latch
 Timer (discrete)
 Standard Discrete Output
 Virtual Discrete Access
 Counter

Miscellaneous Functions
 Loop Mode Select

Value Display
 Mode Select Interlock
 Mode Selection
 Oscillation Monitor
 Look-up Table

continued-

Table 10 - continued

C. OUTPUT CHARACTERIZATION

Output Functions

Uncond. Analog Output
Analog Output (Valve)
Digital Output (Valve)
Uncond. Discrete Output
Digital Valve C_v

Special Output Functions

Start-Stop Output
Optional Discrete Output

Alarm Outputs

Signal Alarm Output
Dev. Alarm Output
PV Alarm Output
Rate Alarm Output

D. CONTROLLER TEST OUTPUT

Self-Test Alarm Output
Comm. Alarm Output

E. STORE FUNCTIONS

Signal Scaling & Store
Signal Scaling & Trend

TABLE 11 EXAMPLES OF SPECIFIC PROCESS CONTROLS

- **Relative humidity internal to the EDCM by controlling coolant temperature**
- **EDC module current**
- **Sabatier reactor temperature**
- **Sabatier reactor cooling air flow**
- **CO₂ reduction water accumulator emptying**
- **Water electrolysis module temperature**
- **Water electrolysis module current**
- **Water electrolysis system pressure**
- **Water supply tank refilling**
- **Transition sequencing**

specific candidate control functions needed for the ARS which would be incorporated at the subsystem controller level.

In order to establish a bound on C/M I requirements, those for various ARS subsystems were established. These are shown in Table 12. Of key importance is the identification of the number of subsystem signal inputs and outputs (both analog and digital and the resulting requirements for signal conditioning). This listing assumed a selected technique or piece of hardware for a particular function (e.g., CO₂ removal by the EDC). The C/M I requirements determined by this table should be applicable, in a general way, to any selected approach.

C/M I Performance Goals

It was assumed that subsystem controllers, of a similar generic design would exist at the lowest functional level. For an integrated ARS there would be one controller. A distributed ARS approach would require three or four. For an integrated ECLSS approach, perhaps four or five. Each controller would handle signal conditioning and localized control and monitoring. Higher level functions, including data storage, communications, supervisory control and fault diagnostics would be handled by higher level controllers. Under this premise, the goals for this generic lower level controller were established and are given in Table 13.

ARS DESIGN FOR SPACE STATION

The ARS for the Space Station is presently being defined by NASA and its contractors. Competing subsystem technologies are being evaluated by both analysis and test. Based on the approach taken under this program for a regenerative ARS, a preliminary design for a Space Station ARS has been prepared. It is documented in a separate report. (15)

The requirements for the ARS as part of the Space Station ECLSS are summarized in Table 14. (16) The fail-operational criterium provides the ability to sustain a failure and retain full operational capability for safe mission continuation. The 21-day emergency requirements are those acceptable if a second, consecutive failure occurs in non-maintainable equipment. It may be, however, that the causes specified for acceptance of these should be redefined because of the minimum ten year in-orbit life requirement of the Space Station. The Space Station will be functionally different than all prior space vehicles and careful consideration must be given to acceptable, degraded and emergency levels in light of its ten year or more life. These requirements will impact the ARS in terms of maintainability and replacement concepts, the degree of integration and, of course, the inherent life and reliability of the major components.

The ARS is projected to be an integrated system comprised of major and supporting components providing the function of CO₂ removal, CO₂ reduction, O₂ generation, cabin humidity control and water handling. A schematic for such a system is shown in Figure 28. A four-person capacity system would be

TABLE 12 C/M I REQUIREMENTS FOR ARS SUBSYSTEMS

Requirement	Subsystem				
	Integrated ARS	EDC	S-CRS	OGS	NSS
Power Supply Voltage, VDC	28	28	28	28	28
Output Voltages, VDC					
+5	X	X	X	X	X
±15	X	X	X	X	X
+28	X	X	X	X	X
<u>Signal Inputs/Outputs</u>					
<u>Analog Inputs</u>					
Cell Voltages (-0.5 to 2.5 V)	18	6	--	6	--
Hi-level (-3 to 10 V)	32	17	3	7	5
Lo-level (0 to 100 mV)	16	5	4	6	6
Thermistor/RTD	9	4	--	2	--
Total	75	32	7	21	11
<u>Digital Inputs</u>					
Front Panel	6	4	4	6	4
External	2	2	2	2	3
Subsystem	8	2	5	8	8
Total	16	8	11	16	15
Analog Outputs (0-5 V)	7	3	2	2	--
<u>Digital Outputs</u>					
Front Panel	9	9	8	9	9
External	2	2	2	2	2
Subsystem	15	4	6	13	12
Total	26	15	16	24	23
<u>Signal Conditioning Cards</u>					
Pressure	4	1	1	2	2
Temperature	5	3	2	2	2
Flow	1	1	1	--	--
Speed	1	--	--	--	--
Cell Voltages	5	2	--	2	--
Controllers	3	2	1	2	1
Drivers	1	1	1	2	1
Built-in Diagnostics	1	1	1	1	1
Others (e.g., LVDT)	2	1	--	--	--
Total	23	12	7	11	7

continued-

Table 12 - continued

Requirement	Subsystem				
	Integrated ARS	EDC	S-CRS	OGS	NSS
Computer					
No. Cards	9	9	8	8	8
No. Control Loops	9	2	1	4	3
Memory Size, K Bytes	36	20	12	20	16
EPROM	24	12	8	12	12
RAM	12	8	4	8	4
Physical					
Connector (Pin No.)					
Power	7	5	3	3	5
Actuators/Outputs	57	25	16	30	30
Sensor/Inputs	160	80	25	50	25
External I/O	7	7	7	7	7
Communication Link	25	25	25	25	25
Size, in					
H	7.4	7.4	7.4	7.4	7.4
W	19.0	15.3	15.3	15.3	15.3
D	15.6	15.6	16.6	15.6	15.6
Weight, lb	40	30.5	27	30	28

TABLE 13 PRELIMINARY SUBSYSTEM CONTROLLER GOALS

Performance Goals

1. Warmup Time	Less than 30 s
2. Sensor Sample Frequency	10/s/sensor
3. Sensor Input Signal	
No.	50
Level	0-5 VDC, 0-10 mV, discrete
4. Actuator Output Signal	
No.	10
Level	0-5 VDC, 5 mA max.
5. Signal Conditioning	
Repeatability	±1% full scale (FS)
Linearity	±1% FS
Accuracy	±2% FS
Drift	±1% FS over 24 hours
Response Time	<1 sec for 90% of FS change
6. Communication Link Data	
Transfer Rate	9,600 baud
7. Interferences	None (e.g., ambient temperature, vibration, EMI)

Operation Goals

1. Unattended Operation	90 days
2. Warmup Time	Less than 30 s
3. Power Type	28 VDC
4. Line Protection	Circuit Breaker
5. Cleanliness	Per RI MA0110-301, Level VC
6. Operating Environment	Temperature, pressure, relative humidity, per MIL-STD-810B
7. Identification and Marking	Per MIL-STD-130D
8. Materials of Construction	Per NASA NHB 8060.1 and SE-4-0006A; RI MC999-0096D
9. Non-Metallic Materials	Per Doc. No. CSD-SS-012
10. Gravity	0-1 G plus launch conditions
11. Noise/Vibration	None/None
12. Cooling	Forced Convection
13. Touch Temperature	<322 K (120 F)

Operating Feature Goals

1. Fail-Operational/Fail-Safe	Automatic shutdown
2. Automated Startup, Shutdown	Electronically controlled
3. Accept Command Inputs	External initiation of operating mode transitions and transfer of control to alternate unit
4. Transmittal of Status	Parameters measured, operating mode and operating mode transition underway.

continued-

Table 13 - continued

Operating Feature Goals - continued

- | | |
|--------------------|---|
| 5. Autoprotection | Reject incorrect commands and detect failures in major components - initiate automatic shutdown |
| 6. Fault Isolation | Transmit codes identifying incorrect commands and component causing shutdown |
| 7. Crew Time | Less than 0.5 h/month |

Packaging Goals

- | | |
|-------------------------------|---|
| 1. Configuration | Self-contained, stand-alone |
| 2. Maintainability | As an LRU with direct access (from top) for LRC's |
| 3. Weight | 6.8 to 9.1 kg (15 to 20 lb) |
| 4. Volume | $<11 \text{ dm}^3$ ($<0.4 \text{ ft}^3$) |
| 5. Packaging Density | $0.72 \text{ to } 0.96 \text{ kg/dm}^3$
(45 to 60 lb/ft ³) |
| 6. Power | $<30 \text{ W}$ |
| 7. Number of Line Connections | 4 (2 to Mechanical, 1 Power, 1 Communication) |
| 8. Reliability | 0.9999 |
| 9. Availability | 99.9% of time/90 days |
| 10. Shelf Life | 10 years |
| 11. Operating Life | 5 years |
| 12. Structural | Shock and vibration resistant |

TABLE 14 ECLSS PERFORMANCE REQUIREMENTS

Parameter	Units	Operational	90-Day Degraded ^(a)	21-Day Emergency
CO ₂ Partial Pressure	Pa (mm Hg)	400 (3.0) Max.	1,000 (7.6) Max.	1,600 (12) Max.
Temperature	K (F)	291-297 (60-75)	286-302 (60-85)	286-305 (60-90)
Dew Point ^(b)	K (F)	277-286 (40-60)	275-294 (35-70)	275-294 (35-70)
Ventilation	m/min (ft/min)	4.5-12 (15-40)	3-30 (10-100)	1.5-60 (5-200)
Potable Water	kg/person (lb/person)	3.1-3.7 (6.8-8.1)	3.1 (6.8) min	3.1 (6.8) min
Hygiene Water	kg/person (lb/person)	5.5 (12) min	2.7 (6) min	1.4 (3) min
Wash Water	kg/person (lb/person)	12.7 (28) min	6.4 (14) min	0
O ₂ Partial Pressure ^(c)	kPa (psia)	2.7-3.2	17-26 (2.4-3.8)	16-27 (2.3-3.9)
Total Pressure	kPa (psia)	101 (14.7)	69-101 (10-14.7)	69-101 (10-14.7)
Trace Contaminants	--	24 h Indus. Std.	8 h Indus. Std.	8 h Indus. Std.
Microbial Count	per m ³ (per ft ³)	3,500 (100)	--	--
Maximum Crew Member	Per Space Station	8	8	12
Maximum Crew Member	Per Habitat Module	4	8	8

(a) Degraded levels meet "Fail Operational" reliability criteria.

(b) In no case shall relative humidities exceed the range of 25-75%.

(c) In no case shall the O₂ partial pressure be below 15.9 kPa (2.3 psia), or the O₂ concentration exceed 26.3%.

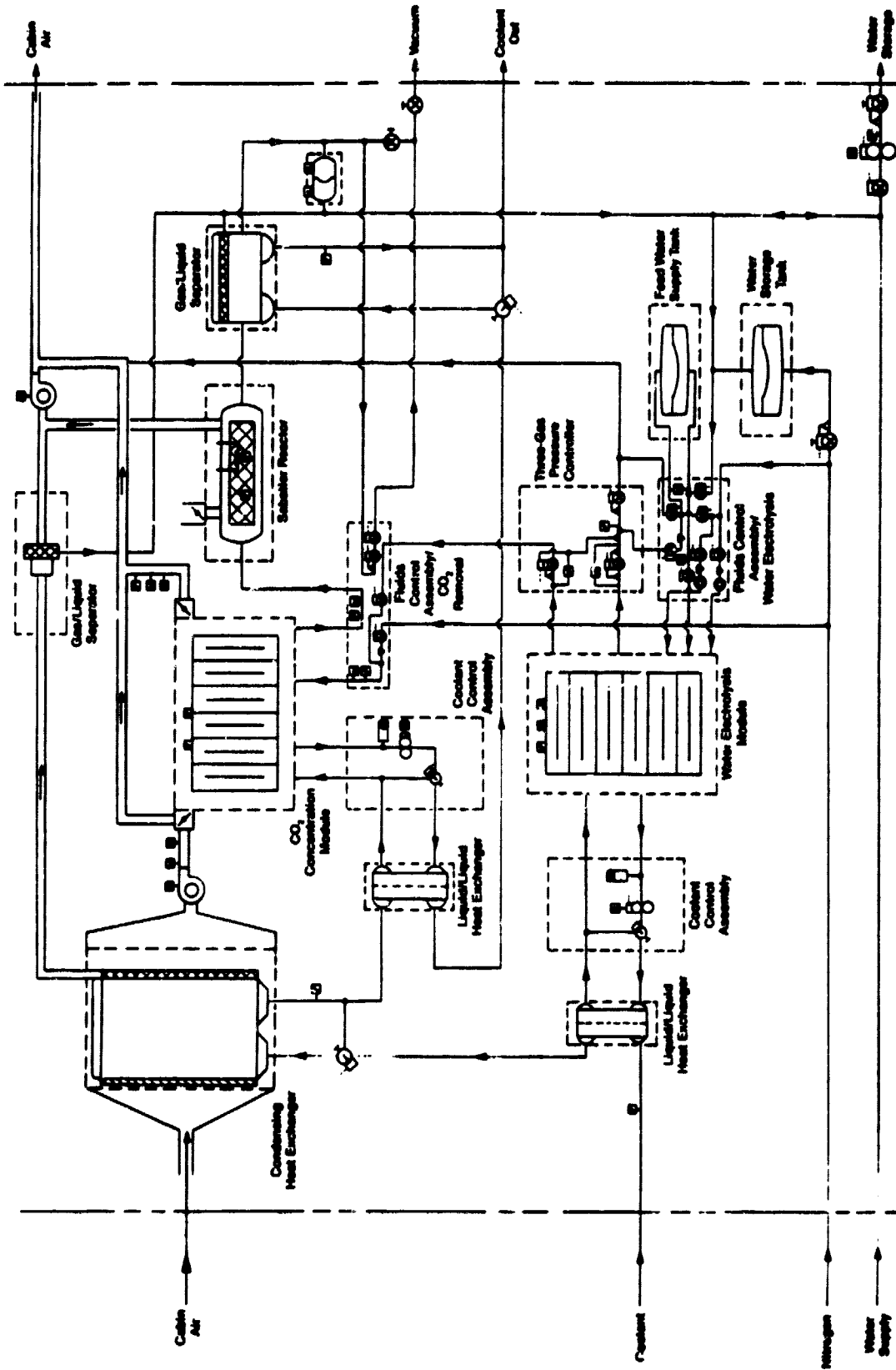


FIGURE 28 AIR REVITALIZATION SYSTEM FOR SPACE STATION

standard. Additional or backup ARS capability would require additional units. Nitrogen supply is not part of the ARS as it would be treated as a spacecraft utility and probably be located in an uninhabitable area.

Interfaces of the ARS with the remaining ECLSS are shown in Figure 29. Principal interfaces will be with the crew compartment (cabin air), water reclamation (for storage/supply) and coolant supply.

CONCLUSIONS

Based on the development and testing of the ARX-1 under this and prior programs the following conclusions are drawn:

1. The ARX-1 defined and built as a breadboard one-person ARS completely performed its intended functions. Its automatic C/M I with its software program permitted the goal of automatic one-button startup from Shutdown to Normal operation to be achieved. The principal functions of CO₂ removal, O₂ generation, CO₂ reduction, cabin humidity control and water handling were successfully demonstrated. The overall program was successful.
2. Prior predicted behavior of the integrated system met the goals that were originally established in terms of removal efficiency, conversion efficiency, etc. The SFWEM met all of its goals of maintaining pressure and generating the proper amounts of H₂ and O₂ when required. The EDCM achieved removal efficiencies in the 70 to 80% area which was desired. Sabatier CO₂ removal efficiency was between 80 and 90%. The CHCS heat exchanger removed close to 100% of the water available to it for a given process air inlet dew point and coolant temperature.
3. There were some problems encountered during the testing. The water handling components and principally the CHCS air/water hydrophobic screen separator did not work satisfactorily throughout the entire portion of the testing. This is one component that needs further development.
4. Overall, the sizing of the components, plumbing, duct work, check valves, regulators, valves orifices (CV) etc. was proper. Nowhere, except in the area of the EDCM inlet ducting, were there indications of pressure buildups due to flow or maldistribution of flow.
5. Even though the breadboard ARX-1 had eliminated many of the interface valving and other components, additional simplification of the system can be achieved. Additional interface valving can be removed (up to six valves). Pressure regulators installed in the system which were of the manual type can be replaced with a permanent set regulator. Many of the manual valves that were provided for ease of component removal or general isolation can be eliminated. Furthermore, as other ECLSS technology development areas have shown,

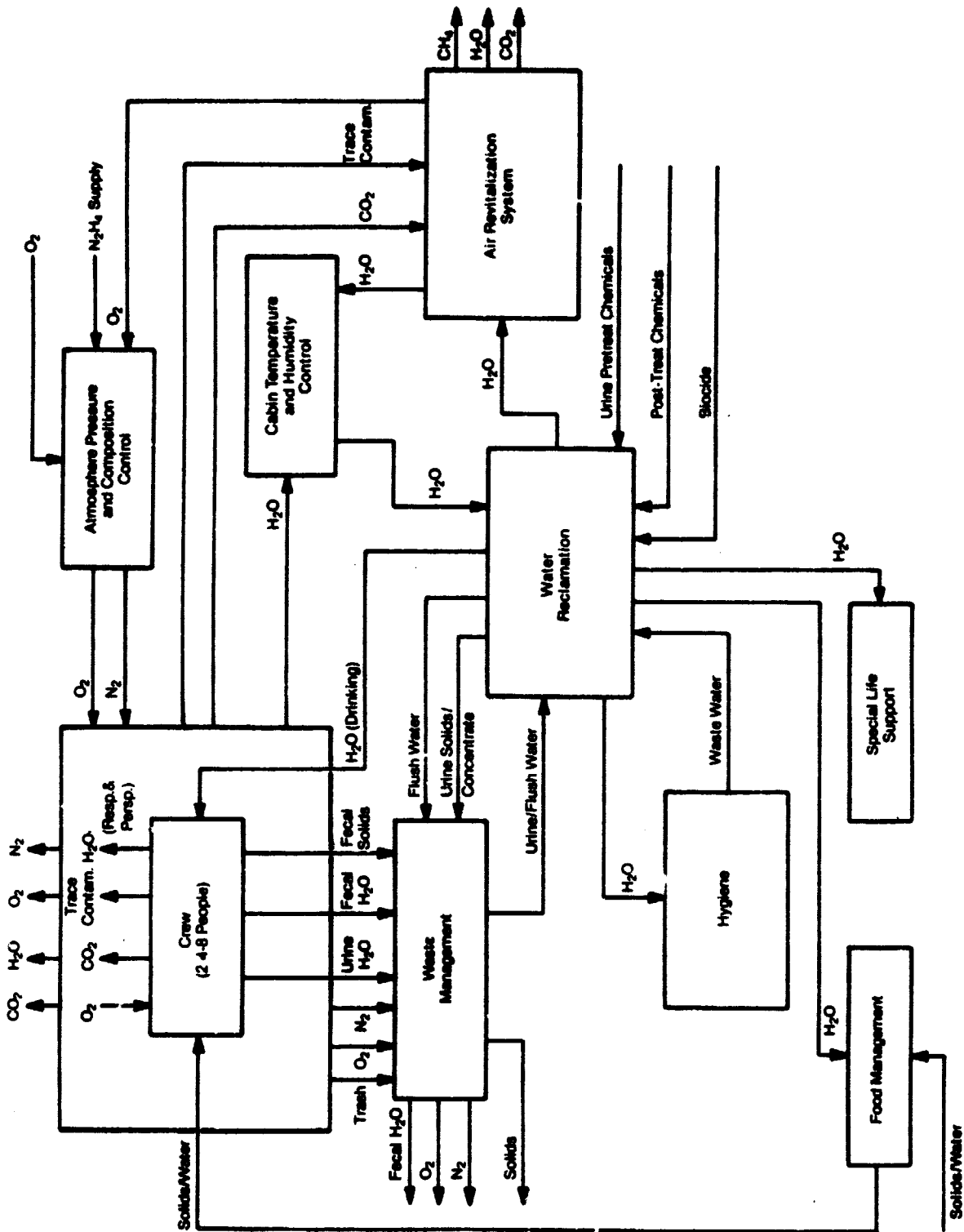


FIGURE 29 SPACE STATION ECLSS BLOCK DIAGRAM

many of the components can be combined into electromechanical assemblies which further simplifies the hardware.

6. There are no limiting ARS integration technologies. Continued improvements in individual components, of course, are desired in both the areas of improved performance and in the development of flight compatible hardware.

RECOMMENDATIONS

The following recommendations are a direct result of the program's conclusions.

1. Integration technology of a regenerative ARS has been demonstrated. A one-person capacity, experimental, laboratory breadboard ARS integrating the functions of CO₂ removal, CO₂ reduction, O₂ generation, humidity control and water handling and distribution hardware has been designed, fabricated, assembled and tested. A centralized automatic C/M I approach for all ARS functions has been implemented. The next step recommended for advancing the ARS technology is to (1) initiate the development of a prototype, one-person ARS leading to a flight experiment to be flown aboard Shuttle/Spacelab, (2) incorporate recent advances in EDC cell configuration and module construction and static feed water electrolysis technology into the prototype ARS, (3) further reduce complexity based on the breadboard system development and (4) maintain the simple one-button start/stop operating mode but with considerable reduction of the electrical cabling needed between the mechanical package and its automated process C/M I by incorporating advanced concepts in signal conditioning and multiplexing.
2. Further simplify the subsystem hardware by combining actuator and sensor functions into single hardware assemblies. For example, in the CO₂ removal area a fluid control assembly (FCA) and a coolant control assembly (CCA) exist which can now be attached directly to the EDCM.
3. In parallel with the prototype ARS, advanced instrumentation and control concepts should be utilized to develop spaceflight worthy C/M I. This C/M I would use the latest technology and advanced concepts in signal conditioning to further reduce the size, power, weight and increase the reliability of the automatic instrumentation required for the ARS.
4. Provide the prototype ARS as a test bed with which considerable endurance testing can be achieved to demonstrate the readiness of integrated regenerative ARS technology in time for the Space Station detailed design and development.

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APPENDIX 1

ARX-1 SOFTWARE MODULE LIST AND CHANGE SUMMARY

Name	Description	Program Modified	
		Yes	No
BASEPG	Base Page Pointers and Data	X	
BUFFER	System Tables and Buffers		X
EQUIDEF	System Definition and Mnemonics		X
SNRDEF	Sensor Definition	X	
AMPLIT	Analog Sensor Amplitude Limiting	X	
CDHNL	Front Panel Command/Data Handler		X
DISPLY	Display the Contents of an ASCII Buffer		X
DSCNTL	Display Control		X
EKOSNX	Echo Input and Syntax Check		X
ELSTMR	EIapse Timer List		X
EXAMIN	Examine Operation of Operator Command		X
FPDSPK	Front Panel Display Package		X
FPRQST	Front Panel Request Service		X
IDSRCH	Sensor Identification Code Search		X
LIGHT	Update the Front Panel Indicator Lamps		X
MODIFY	Modify Operation of Operator Command		X
MSGBUF	Display Message Text		X
OEMSUB	On-line, Examine and Modify Library		X
OPRSRV	Service Front Panel Request		X
SPCRFP	Setpoint Cross-Reference Lookup		X
SKSKEY	System Front Panel Key Service		X
TMRUPD	Timer Counter Update		X
VERIFY	Verify Password		X
AUDIO	Audio Signal		X
BINDEC	Binary to Decimal ASCII Conversion		X
CONST	Adjustable System Constant Table		X
CONVRT	Input Data Conversion		X
ERRCOD	Component Error Request		X
ERRTXT	Text Error Message Request		X
INPUT	All Analog and Digital Sensor Inputs	X	
LIBRY	Subroutine Library		X
LTDSP	Light Display		X
MACSUB	Macro Subroutines		X
OUTPUT	All Analog and Digital Actuator Outputs	X	
OVR^CT	Actuator Override Handler		X
ERTE	Real Time Executive	X	
SCALE	Scale Analog Sensor Value		X
ERCODE	Coded Error Messages		X
ERTEXT	Text Error Messages		X
FDMSG	Fault Message Handler		X
SDCODE	Decode and Sensor Code to ASCII Character Conversion		X
SNRTYP	Sensor Type Decoder		X

continued-

Appendix 1 - continued

Name	Description	Program Modified	
		Yes	No
SPCRFD	Setpoint Cross-Reference for Fault Detection		X
SPFIND	Determine Analog Sensor's Status		X
AB	Normal to Shutdown Transition	X	
BA	Shutdown to Normal Transition	X	
AE	Normal to Standby Transition	X	
EA	Standby to Normal Transition	X	
BC	Shutdown to Purge Transition	X	
CB	Purge to Shutdown Transition	X	
OPCON	Operating Mode Control	X	
PWRUP	Powerup and Power Failure Handler		X
ALIVE	Output a Square Wave to Supplementary Shutdown Controller		X
CCL	Current Control Subroutine		X
CFTC	Coolant Temperature Control Subroutine		X
CHCTMP	CHCS Temperature Control		X
CRID	Corrected Remainder Integer Divide		X
DPN	Double Precision Negate		X
EDCI	EDCM Current Control		X
EDCTMP	EDCM Temperature Control		X
PCL	Pressure Control Loop		X
SBTTMP	Sabatier Temperature Control		X
SYSPRS	System Pressure Control	X	
SYSMOD	System Operating Mode Display		X
TCL	Temperature Control Subroutine		X
VLVSTP	Simulates Mechanical Valve Stops	X	
WESTMP	WES Temperature Control		X
WST1FL	Water Storage Tank #1 Fill Control	X	
WES1	WVEM Current Control		X
WST3RM	Water Storage Tank #3 Removal Control		X

APPENDIX 2

ARX-1 LIGHT/DARK CYCLE MODE TRANSITIONS

Normal to Standby (Light to Dark) (A to E)

1. If water fill control (WST1FL) is running, wait until completed. Note, fill timer disabled.
2. Switch to Standby mode fault detection table.
3. Disable EDCM and SFWEM current control. Close V17, wait 0.3 seconds, verify.
4. Open V16 and V18, wait 0.3 seconds, verify. Wait 30 seconds.
5. Disable 3-FPC system pressure control.
6. Close EDCM inlet valve by energizing motor through V32. Wait 5.1 seconds.
7. Deenergize V32.
8. Close EDCM outlet valve by energizing motor through V35. Wait 5.1 seconds.
9. Deenergize V35.
10. Enable Standby mode.

Standby to Normal (Dark to Light) (E to A)

1. Enable 3-FPC system pressure control.
2. Disable low fault detection on E1-18, I1, I2.
3. Switch to Normal mode setpoint table.
4. Set SFWEM current control to 9.9 to 10.0 A. Open V17, wait 0.3 seconds, verify.
5. Enable SFWEM current control. Wait 1 minute.
6. Enable SFWEM temperature control.
7. Set SFWEM current to 18.9 to 19.1 A. Wait 1 minute.
8. Close V16 and V18, wait 0.3 seconds, verify.
9. Open EDCM outlet valve by energizing motor through V32. Wait 5 seconds.
10. Deenergize V34.
11. Open EDCM inlet valve by energizing motor through V33. Wait 5 seconds.
12. Deenergize V33.
13. Wait until E1 to E6 are greater than 0.8 V, check every 0.2 seconds up to 3 minutes.
14. Enable EDCM current control.
15. Enable low fault detection on E1-E18, I1, I2.
16. Enable EDCM temperature control.
17. Enable Normal mode. Restart fill control timer.